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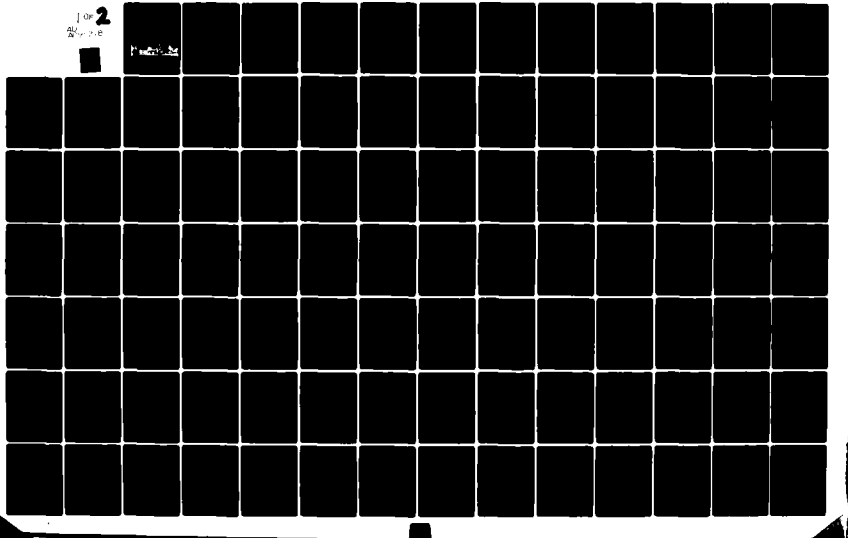

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DEVELOPMENT OF A QUANTITATIVE METHOD TO PREDICT CRITICAL SHEAR STRESS AND RATE OF EROSION OF NATURAL UNDISTURBED COHESIVE SOILS

by

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Cohesive soils
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

To determine streambank recession with time, resulting from erosion due to current action and slope failure, requires measurement of the rate of erosion and shear strength properties of undisturbed natural soils. However, it is recognized that for many streambank erosion problems, it may not be economically feasible to obtain undisturbed soil samples and conduct laboratory tests to measure rate of erosion and shear strength. For this type of problem, it may suffice to determine the susceptibility of the streambank to (Continued)

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20. ABSTRACT (Continued).

erosion and slope failure, without determining the bank recession at selected intervals of time.

The study was conducted in an attempt to develop a quantitative method to predict the hydraulic shear stress at which erosion is initiated (critical shear stress) and the rate of erosion of natural soil (with sufficient cohesiveness to allow undisturbed samples to be taken) along the streambank. In order to obtain a wide range of properties with sufficient geographical distribution, soil and river water samples were requested from Corps of Engineers (CE) Districts in the United States. Preliminary tests conducted on 42 samples included: (a) free swell test on undisturbed soil; (b) dielectric dispersion on remolded soil; (c) slaking test on undisturbed soil; (d) amount of clay present in soil; (e) soil chemistry (pH and soluble cations); and (g) river water chemistry (pH and soluble cations). Based upon the results of the preliminary tests 30 soils were selected for detailed analysis which included : (a) index property tests (hydrometer analyses, specific gravity, organic content, gypsum content, moisture content, unit weight, and Atterberg limits); (b) soil chemistry (exchangeable cations); (c) dielectric dispersion on undisturbed soil; (d) flume erosion tests on undisturbed soil; and (e) rotating cylinder erosion tests on saturated remolded soil..

The results of the study showed that remolding the soil generally decreased both the critical shear stress and the rate of change of erosion rate. The salt concentraton of the eroding fluid significantly influenced the erosion of remolded soil samples. Usually, as the salt concentration of the river (eroding) water decreased, the critical shear stress of the soil decreased, and the rate of change of erosion rate increased.

The results of the study did not yield a quantitative method to predict critical shear stress and/or rate of erosion for undisturbed natural soils. However, it was shown that a previously developed chart for remolded soil (Figure 3) gave a predicted value of critical shear stress that was generally less than the measured value for undisturbed soil using distilled water as eroding fluid. Since the critical shear stress usually increases as the salt concentration of the eroding fluid increases, the chart should give a reasonable estimate of the critical shear stress for a natural undisturbed soil subjected to hydraulic shear stress from river (eroding) water. Using the estimated critical shear stress, a predictive chart (Figure 10), which was developed in this study of the relationship between critical shear stress and rate of change of erosion rate for undisturbed soil, with distilled water as the eroding fluid, can be used to estimate the rate of change of erosion rate for a natural undisturbed soil subjected to hydraulic shear stress from river (eroding) water. The estimated rate of change of erosion rate will represent an upper bound because as the salt concentration increases, from distilled water to river water concentration, the rate of change of erosion rate decreases.

PREFACE

The work described in this report was performed under Contract No. DACW 39-77-C-0080 entitled "Development of a Quantitative Method to Predict Critical Shear Stress and Rate of Erosion of Natural Undisturbed Cohesive Soils," between the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, and the University of California at Davis, Davis, California. The research was conducted during the period September 1977 to January 1980 as part of the Streambank Erosion Control and Demonstration Act of 1974 (Public Law 93-251, Section 32, as amended by Public Law 94-1755, Section 155 and 161), Task 1 Work Unit 04.

The report describes the results of erosion and soil characterization tests performed on cohesive soils. Appendices to the report include plots of shear stress versus erosion rate for remolded and undisturbed soils.

The principal investigator for the study was Dr. Kandiah Arulanandan. Ernest Gillogley and Ryan Tully organized the study and helped prepare the report. Ronald Heinzen and Ranjan Ariathurai provided technical advice. Annalingan Anandarajah, Kandiah Arulmoli, Ernest Gillogley, Douglas Jackson, Samuel Parino, James Richardson, Ryan Tully, Edward Uhlir, and Kathy Young performed the study.

The study was monitored by Dr. Edward B. Perry under the general supervision of Mr. Clifford L. McAnear, Acting Chief, Geotechnical Laboratory of the WES.

COL John L. Cannon, CE, and COL Nelson P. Conover, CE, were Directors of the WES during the conduct of this study and preparation of this report. Mr. F. R. Brown was Technical Director.

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APPENDIX I: GLOSSARY I.1

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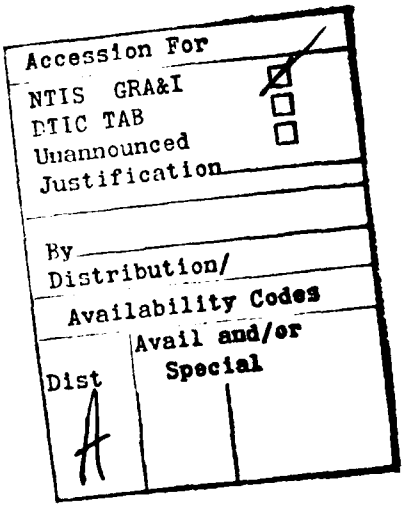

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
cubic feet per second	0.02831685	cubic metres per second
feet	0.3048	metres
feet per second	0.3048	metres per second
gallons (U. S. liquid)	3.785412	cubic decimetres
inches	25.4	millimetres
pounds per cubic feet	16.01846	kilograms per cubic metre

DEVELOPMENT OF A QUANTITATIVE METHOD TO PREDICT CRITICAL SHEAR STRESS AND RATE OF EROSION OF NATURAL UNDISTURBED COHESIVE SOILS

PART I: INTRODUCTION

Background

1. Soil erosion is a complex phenomenon affected by many different parameters. One step toward understanding the soil erosion process is to determine which soil characteristics control its erodibility in terms of a time rate of soil-loss from a given soil surface area under a uniform hydraulic shear stress.

2. The soil parameters which are known to effect erodibility of non-cohesive and cohesive soils differ substantially. The erodibility of non-cohesive soils is controlled by gravitational forces and soil parameters such as grain size distribution, particle density and grain shape. A detailed survey of the erosion of non-cohesive soils has been presented by Graf (1). Cohesive soil erosion is controlled by physical and chemical surface phenomenon such as the structure and particle bonding of the soil and interaction with the pore and eroding fluids (2). The erodibility of cohesive soils is affected by the following characteristics:

a. Amount and type of clay fraction.
b. Chemical composition of the pore fluid.
c. Content of organic matter, gypsum and other cementing agents.
d. Grain size distribution of non-cohesive portion.
e. Placement conditions, Thixotropy, and stress history of the soil.
f. Soil pH, temperature, and water content.
g. Chemical composition, temperature, and pH of the eroding fluid.

The fact that cohesive soil erosion is essentially a surface phenomenon explains why bulk engineering properties of soils such as vane shear strength, unconfined compressive strength, and dry unit weight have not proved useful as erosion predictors (3,4,5).

3. The interest of this report lies mainly in the erodibility of natural undisturbed cohesive soils. Previous work by Kandiah (6), Alizadeh (7), Maller (8) and others have shown reliable relationships between the erodibility of saturated remolded cohesive soils and the following soil and eroding fluid characteristics:

a. Type and amount of clay as characterized by the soil cation-exchange capacity (CEC) or the magnitude of dielectric dispersion ($\Delta\varepsilon_o$).
b. Pore fluid salt concentrations in terms of total salt concentration (meq/ℓ) and sodium adsorption ratio SAR, where

$$SAR = (Na^+)/\sqrt{\frac{(Ca^{++}) + (Mg^{++})}{2}}$$

c. Soil paste pH.
d. Organic matter content.

4. Alizadeh and Kandiah have presented correlations between soil erodibility and degree of free swell of a soil. The basis of the relationship is that the strength of the soil structure is a major factor affecting both processes. The free swell test consists of placing a saturated soil sample on a spc .e saturated in distilled water. The osmotic gradient between the pore fluid and distilled water creates a tendency for water to move into the soil. The strength of the soil structure tends to limit structure deformation and control the degree of water uptake. The degree of free swell is defined as the weight of water uptake per 100 grams of dry soil.

5. Heinzen (9) compared the erodibility of eleven natural undisturbed soil samples, as determined by laboratory erosion tests, with various soil parameters. The most consistent and useful correlations were found between soil erodibility and type and amount of clay and pore fluid composition. Results of free swell as well as dispersion ratio tests, as defined by Middleton (10), proved useful as general guides to approximating the erodibility of undisturbed cohesive soils.

6. Soil erodibility in previous work (6,7,8,9) has been measured in either a flume or rotating cylinder device. While the rotating cylinder device has been used to accurately determine erodibilities of saturated cohesive soils, the flume has been found to give more useful test results for partially saturated soils (9). The erodibility of a given soil can be characterized by

both the critical shear stress, τ_c and the erosion rate, $\dot{\varepsilon}$. The critical shear stress is defined as the shear stress at which erosion of the soil is initiated. At shear stress levels below the critical shear stress relatively little erosion takes place. The erosion rate is defined as the slope of a line which best fits a plot of soil erosion, in terms of weight lost (gm/cm^2-min) versus shear stress ($dynes/cm^2$), for shear stresses greater than the critical shear stress. The most consistent results and best correlations with other soil parameters have been obtained using only critical shear stress to characterize soil erodibility.

Effect of Soil Structure and Water Content on Slaking

7. The rate of soil loss of partially saturated samples when immersed in water can be very high even with no shear stress acting on the soil surface. This type of soil particle removal under zero eroding fluid shear stress is commonly termed slaking or flaking. Kandiah and Arulanandan (11) and others (12,13) have shown that the rate of slaking is affected by the structure of the soil. The soils with stronger flocculated clay structures slake less. This dependency of slaking on soil structure indicates that a slake test could give an indication of the erodibility of a soil. Moriwaki and Mitchell (14) have found that the slaking rate of soils is also affected by the water content of the soil before immersion in the water. The drier the sample before immersion, the greater was the slaking rate.

8. It is this slaking mechanism which makes it difficult to apply soil erosion versus shear stress relationships to rotating cylinder tests on partially saturated soils since the erosion surface of rotating cylinder samples is vertical, as opposed to a nearly horizontal erosion surface of flume test samples.

Objective of the Proposed Study

9. The important need to understand how various factors affect the complicated process of soil erosion is obvious when considering the extent of steambank erosion in the United States. The objective of this study is to find reliable relationships correlating the erodibility of many undisturbed cohesive soils sampled from various streambanks across the nation to soil composition and structure and eroding water composition as determined by relatively quick laboratory tests. Such correlations could then be used to approximate the relative soil erodibilities from simple laboratory tests.

Testing Program

10. Samples from 42 different streambank sites were collected across the nation by various Districts of the U.S. Army Corps of Engineers and sent to the Soil Mechanics Laboratory at the University of California at Davis for testing. Approximately half the samples were taken from stable sites where erosion was not considered to be a problem. The other half were taken from sites where significant erosion was causing problems with bank stability. Each sample consisted of both undisturbed and disturbed soil and 3 gallons of river water (eroding fluid), taken from the stream adjacent to the site. A summary of the locations from which the samples were taken, the sample identification numbers, the District which sent them, the date they were received and the field erodibility observations is presented in Table 1.

11. A preliminary analysis was performed on all 42 of the soil samples. From the results of these tests, 30 soils were selected for further testing of soil composition and erodibility. The selection was based on a requirement that the soil have at least 5% clay (finer than 0.002 mm) and on an attempt to include the full variety of clayey soil types received. The following is a summary of the tests performed as part of the preliminary analysis:

a. Hydrometer analysis to determine grain-size distribution, i.e. percent clay-sized fraction.

b. Determination of the magnitude of dielectric dispersion on both undisturbed and saturated remolded specimens to characterize the type and amount of clay.
c. Determination of the pore fluid composition (SAR, total salt conc., pH).
d. Determination of the river water (eroding fluid) composition (SAR, total salt conc., pH).
e. Cation-exchange capacity test.
f. Free swell tests on saturated undisturbed samples.

12. A summary of the first year's testing program for the 30 selected soils is given below.

a. Moisture content determination.
b. Undisturbed density determination.
c. Specific gravity tests.
d. Atterberg Limit tests.
e. Organic content determination.
f. Gypsum content determination.
g. Flume tests on saturated undisturbed samples using distilled water as an eroding fluid.
h. Rotating cylinder tests on saturated remolded samples using three different eroding fluid total salt concentrations, the highest concentration being that of the eroding fluid of particular sample (river water concentration).
i. Slake tests on saturated undisturbed samples.

13. Initially, the preliminary analysis was to include slake tests on undisturbed samples of all the soils. Since some of the samples were very sandy, it was not necessary to perform the slake test on these samples. For this reason, the slake tests were performed on the 30 selected soils only. Because the selected 30 soils were clayey in nature, it was considered unnecessary to perform the sieve anlaysis test initially planned.

PART II: TESTING PROCEDURES

Flume Apparatus Description

The flume

14. The recirculating flume (Figure 1) has a clear plexiglass channel 8 feet long, 6 inches wide and 12 inches deep. The flume has three controls for varying the velocity of fluid flow: a discharge control valve, slope adjustment operated by a motor drive and tail-gate position. During erosion studies the slope varies from 0 to 4%. These conditions give average fluid velocities of up to 4.06 ft/sec, flow depths varying from 1/4 to 3/4 inch and an average discharge of 0.127 cfs.

15. Distilled water is pumped from a 60-gallon capacity reservoir below the channel bed. The temperature of the water is controlled by passing tap water through heat exchangers placed inside the reservoir. The reservoir is drained and refilled periodically in order to keep the conductivity below 20 micromhos/cm. This corresponds to a total salt concentration of about 0.2 meq/ℓ.

The manometers

16. Two glass manometers are mounted on the flume. A verticle mercury manometer is used to measure the pressure difference across an orifice plate between the pump and discharge control valve. This has been calibrated to determine discharge flow rates. An inclined carbon tetrachloride manometer is used to measure the velocity head of the flow at the position of a pitot tube. A slight amount of oil base dye is added to the carbon tetrachloride to make the water interface distinguishable. A second set of tubes connecting both sides of the inclined manometer to an elevated water reservoir is used to blow air out of the lines before making manometer readings. When manometer readings are made, valves between the manometer and the elevated reservoir remain closed. Both manometers have a main manometer valve. When this valve is closed no flow is allowed through the manometer.

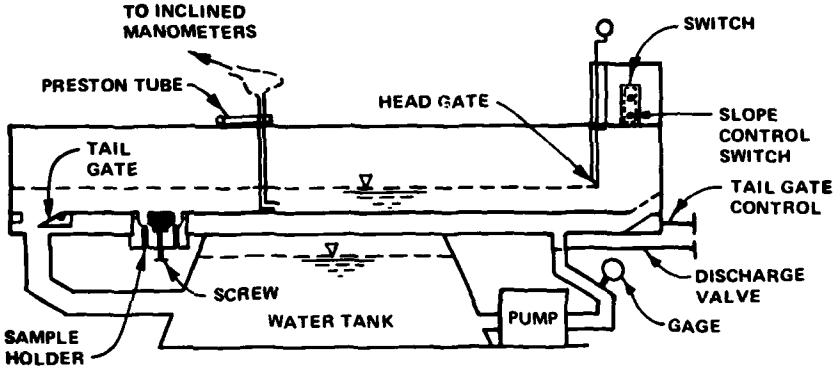

Figure 1. Schematic Representation of Laboratory Recirculating Hydraulic Erosion Flume.

The soil sample

17. The soil sample is contained in a thin-walled (0.04 inch) aluminum tubing, 3.9 inches long and three inches in outside diameter. The tubing inserts into the channel bed centered at a point five feet downstream of the beginning of the channel bed. A hole in the channel bed is sized so that the tubing fits snugly and will create minimum disturbance to flow when the tubing top is inserted flush with the channel bed. A sample holder which houses the sample tubing during testing is mounted just below the hole in the channel bed.

Velocity head measurement

18. A 1/4 inch outside diameter pitot tube is used to measure the velocity head of the flow at certain points. The pitot tube is mounted to a brass sleeve which can be raised or lowered to make small adjustments on the verticle position of the pitot tube. The brass sleeve is fastened to an assembly, mounted on the top of the channel, which can swing the pitot tube clear of the channel bed when not in use. The velocity head reading is converted to a channel bed shear stress with an equation developed by Preston (15) (See next section).

Shear Stress Calibration of Flume

19. The shear stress acting on the soil surface being eroded in the recirculating flume is not measured directly but approximated from relationships with the velocity head near the soil surface. The velocity head is measured with a 1/4-inch diameter pitot tube (about 4 mm above the soil surface) connected to a glass carbon tetrachloride manometer.

20. The manometer is inclined at an angle sufficient to give a full-scale pressure difference for maximum flow of the flume. Known pressures are applied to the pitot tube to calibrate the inclined manometer for velocity head determinations.

21. An empirical equation developed by Preston (15) is used to approximate the bed shear stress from the velocity head reading of a pitot tube resting on the channel bed or soil surface. The equation was presented by Preston as follows:

$$\text{Log}\ \frac{\tau_o\, d^2}{4\rho\, \nu^2} = -1.396 + \frac{7}{8}\ \text{Log}\ \frac{(P_t - P_o)\, d^2}{4\rho\, \nu^2}$$

For

$$4.5 < \text{Log}\ \frac{(P_t - P_o)\, d^2}{4\rho\, \nu^2} < 6.5$$

where

τ_o	is the bed shear stress (dynes/cm^2)
d	is the outside diameter of the pitot tube (cm)
ρ	is the mass density of the fluid (gm/cm^3)
ν	is the kinematic viscosity of the fluid (stoke or cm^2/sec)
P_t	is the total head measured (dynes/cm^2)
P_o	is the static head measured (dynes/cm^2)

Results using Preston's equation were checked against other methods of approximating bed shear stress over the surface of the soil sample as a check on the reliability of the equation.

22. The pressure range over which this relationship was developed corresponds to approximated shear stresses in the flume equal to or less than 14.6 dynes/cm^2. All shear stress approximations greater than this (up to 45 dynes/cm^2 for this study) are extrapolated from Preston's original data and may be progressively less accurate (± 5 percent at 45 dynes/cm^2).

23. The surface of a soil sample is simulated during flume calibration by using a plastic plug with soil glued to the surface, creating a roughness similar to that of an eroding soil sample. The pitot tube was placed on the soil surface at various locations to check for a uniform distribution of shear stresses across the surface. The shear stress determined at the extreme downstream end of the sample was found to be nearly equal to the average shear stress on the sample.

24. In an attempt to decrease possible disturbance to flow, a smaller 1/8 inch diameter pitot tube of similar design was also used during the initial calibration of the flume. After a few tests it was decided that too much time was required for the manometer reading to come to equilibrium when using the smaller pitot tube.

25. The 1/4 inch diameter pitot tube is clamped to a sleeve which can be adjusted to raise the pitot tube above the surface of the channel bed. The pitot tube is raised about 4 mm above the soil surface during the erosion tests, allowing velocity head readings to be taken near the soil surface while eroded particles are carried away under or to the side of the tube. Clogging of the pitot tube with eroded soil particles is avoided, shear stress can develop, and the erosion process can continue unobstructed during the entire test.

26. Calibration of the manometer reading to approximate the shear stress acting on the soil surface during the erosion tests is achieved by taking velocity head readings at a point on the soil surface of the plastic plug located at the extreme downstream end of the sample and at a point 4 mm above the first for the same flow condition. The temperature of the eroding fluid (distilled water) is recorded during calibration and the appropriate density and viscosity are read from standard charts. Preston's equation is used to convert the surface reading to a shear stress. The manometer reading from the raised position is then plotted against the determined shear stress for various flows. A linear relationship is found to exist for a constant flume bed slope. A series of plots determined for various slopes and covering the full range of shear stresses developed in the flume are used to approximate shear stresses for all the flume erosion tests. The reading on the mercury manometer corresponding to each measured shear stress for a given flume slope is included on the calibration plot. This serves as a guide to determining how much to open the discharge valve at the beginning of an erosion test to obtain a desired critical shear stress level.

27. Shear stress calibration of the pitot tube using the soil surfaced plastic plug was carried out before erosion testing started and after two-thirds of the soils were tested. Calibration plots for shear stresses less than

16 dynes/cm^2 were consistently repeatable within a tenth dyne/cm^2. Plots for shear stresses greater than 16 dynes/cm^2 were repeatable within four tenths dyne/cm^2. What little variation occurred can be attributed to minor shifts in the position of the pitot tube.

28. A factor which may reduce the accuracy of higher shear stress approximations is the roughness of the soil surface after some erosion has taken place. During erosion tests the undisturbed soil surface is first eroded at a low shear stress. The subsequent flume runs erode the sample at progressively higher shear stresses. When it is possible, the surface of the undisturbed soils severely roughened by the erosion of irregular soil chunks is made smooth again before further testing. This is difficult to do for some samples. Although this problem can significantly affect the slope of the erosion rate versus shear stress plot for the troublesome soils, the effect on the determined critical shear stress is considered minor.

29. The eroding fluid temperature is controlled during calibration and erosion testing by passing tap water through heat exchangers in the flume reservoir. The tap water temperature was about 20° C, $\pm$ 3°. In this way, warming of the eroding fluid by heat generating from the flume pump during the erosion testing was limited to less than six tenths of one degree centigrade during each test. Some temperature variation did occur from day to day due to fluctuations in the tap water temperature. Eroding fluid temperatures of some of the erosion tests were as much as three degrees lower than the temperature at which the shear stress calibration was made. The error in shear stress determinations due to this is less than three percent. This is small with respect to the accuracy which can be expected in the flume erosion tests.

30. Considering the limitations involved, when the soil surface is flat and level with the channel bed, shear stress approximations less than 15 dynes/cm^2 can be expected to be accurate within a dyne/cm^2. Shear stress approximations greater than 15 dynes/cm^2 are extrapolations of Preston's equation and may be progressively less accurate as shear stresses increase.

Flume Test Procedure

Sample preparation before wetting

31. Undisturbed soil samples are obtained by forcing a thin walled (0.04 inch thick) aluminum tubing, 3.9 inches long with a 3.0 inch outside diameter, into the soil. Before this the inside of the tubing is greased to reduce soil disturbance and improve the seal between the sample and the tubing. The outside diameter at the bottom edge of the tubing is tapered to aid in cutting into the soil. When about 2 to 2½ inches of undisturbed soil has been penetrated, the tubing is separated from the rest of the sample. The sample is pushed up through the tubing so the top exposed surface can be trimmed level to the tubing edge with a wire cheese cutter or a fine hacksaw blade, depending on how hard the soil is. After the top surface is trimmed, the sample is pushed back down through the tubing so the bottom exposed surface can be trimmed. A water content determination is made on the removed soil, and the weight and dimensions of the trimmed sample are recorded to determine the undisturbed moist density.

Sample wetting

32. The trimmed sample is placed in a 1000 ml glass beaker with the bottom surface resting on a filter paper and porous stone. The beaker is then filled with distilled water, wetting the sample from the bottom up. Although the water level outside the tubing is raised above the soil surface level for samples which are difficult to saturate, care is taken that deep water ponding on the soil surface is kept to a minimum. The process is considered complete when the entire soil surface glistens with a thin layer of free standing water. The sample tubing is removed from the beaker after wetting is completed and weighed immediately. The time required to wet the sample and the weight of water gained are recorded.

Sample preparation after wetting

33. The undisturbed soil is pushed up in the tubing with a thin (1/4 inch thick) plastic disc placed on the bottom surface so the top surface is again level with the top edge of the tubing. A rubber "0" ring seated in a groove around the circumference of the disc fits tight against the inside of the

aluminum tubing when the disc is inserted. This disc supports the soil sample during erosion tests. The plastic disc remains beneath the soil sample until the erosion testing is complete.

34. The sample tubing is then inserted into the flume and pushed down until the tubing top edge and soil surface are level with the channel bed. With the channel slope at one percent or less, and a plug inserted in the channel drain, the bed is filled to a 1/2 inch depth, and the sample is allowed to soak under these conditions for ten minutes. A shield is placed just upstream of the soil surface to protect the soil from flow surges while the channel is being filled. When starting each erosion or soaking test, the flume pump is always turned on before opening the discharge valve. After each test the discharge valve is always closed tight before turning off the pump. This keeps the pump primed at all times. One half inch is a typical depth of flow during an erosion test. After 10 minutes the drain is unplugged, the shield is taken away from the soil surface, and the sample tubing is removed from the flume. This is done by using the base screw below the sample holder to force the tubing up until it is high enough to be pulled completely out by hand from above.

Determination of the water uptake rate after soaking

35. After removing the sample from the flume, it is tilted enough to drain off all the free surface water. The sides of the tubing are then dried off with paper tissues. After this brief drying the sample is weighed. It is important that the time which elapses from when the sample is removed from the flume to when it is weighed, as well as the drying procedure before and after each soaking and erosion test, be repeated as close as possible each time to produce consistent weight loss results. A one minute drying time is kept as a standard.

36. In order to determine the rate at which water weight is gained by the soil sample, it is again soaked in the flume under a 1/2 inch water depth using the same technique as mentioned above. After only 2 1/2 minutes

of soaking, the sample tubing is removed, dried as before, and weighed. This soaking test is done once just before the first erosion test, once half way through, and once just after the last of several erosion tests performed on each soil sample. Changes in the rate at which water weight is gained is considered in calculating the soil weight loss during each erosion test by linearly interpolating between soaking tests.

Final sample preparation

37. Final preparation of the soil surface involves inserting the sample back into the flume so the soil surface is flush with the channel bed and carefully eroding off any loose or disturbed soil. When all the disturbed soil has been carried away, the discharge valve is closed, and the sample tubing is removed from the flume, dried, and weighed. This final preparation is repeated after each soaking test.

Erosion test - shear stress measurement

38. The sample tubing is placed into the channel bed taking particular care that the soil surface and top edge of the tubing are made flush with the channel bed. The shield is placed just upstream of the soil surface, and the channel drain is plugged before slowly opening the discharge valve. Prefilling the channel before the start of an erosion test protects the soil surface from high shear stress surges which would occur if the erosion flow was started with an empty channel. The discharge valve is closed as the soil surface is submerged by 1/2 inch of distilled water, and the shield is removed from the sample. Previous to this point the pitot tube has been swung up away from the channel bed. The tube is now lowered to 4 mm above the soil surface, submerging the pitot tube inlets. Any air caught in the pitot tube lines is blown out with a small release from an elevated reservoir connected to the pitot tube lines. The main inclined manometer valve is kept closed at this time.

39. The erosion test is started by simultaneously opening the discharge valve to allow a certain desired flow rate as indicated by the mercury manometer reading and unplugging the channel drain. The first erosion tests on each sample are performed at low flow rates, applying low shear stresses to the sample. Subsequent tests are performed at increasing shear stresses.

40. Each erosion test is continued for 2½ minutes. Immediately after opening the discharge valve, the main inclined manometer valve is opened allowing the manometer reading to come up to equilibrium with the pressures acting on the pitot tube. This usually takes about a minute. After the inclined manometer reading is taken, the main manometer valve is again closed. During the first minute of each test a temperature reading of the inclined manometer is recorded. After 2½ minutes the discharge valve is closed, and the pitot tube is raised away from the soil surface. The sample tubing is removed from the flume, dried, and weighed. The length of the test is recorded to the nearest second.

41. The average erosion rate occurring during each erosion test is calculated directly from the weight loss of the soil sample, the known inside cross-sectional area of the sample tubing and the time length of the erosion test. The actual weight of soil lost by the sample is determined by adding the total sample weight change during each test to the approximate water weight gained by the sample.

42. Erosion tests are repeated at increasing shear stresses until enough data is obtained to produce a repeatable plot of shear stress (dynes/cm^2) versus erosion rate (gm/cm^2-min). This varied from 5 to 10 erosion tests per soil.

43. After the last erosion test, a water content determination is made on the top 1/4 inch of the soil. Also, the conductivity of the reservoir water is checked to make sure the eroding fluid does not exceed 20 micromhos/cm limit (≅ distilled water).

Rotating Cylinder

Rotating cylinder description

44. The rotating cylinder (Figure 2) is a hollow plexiglass cylinder with an inside diameter of nearly 4 inches. The cylinder is supported axially on an electric motor driven shaft. Soil samples are supported by a vertical rod and are positioned inside the rotating cylinder so that the vertical axis of the soil supporting rod is coincident with the vertical axis of the rotating cylinder. The annulus between the rotating cylinder and the soil sample is filled

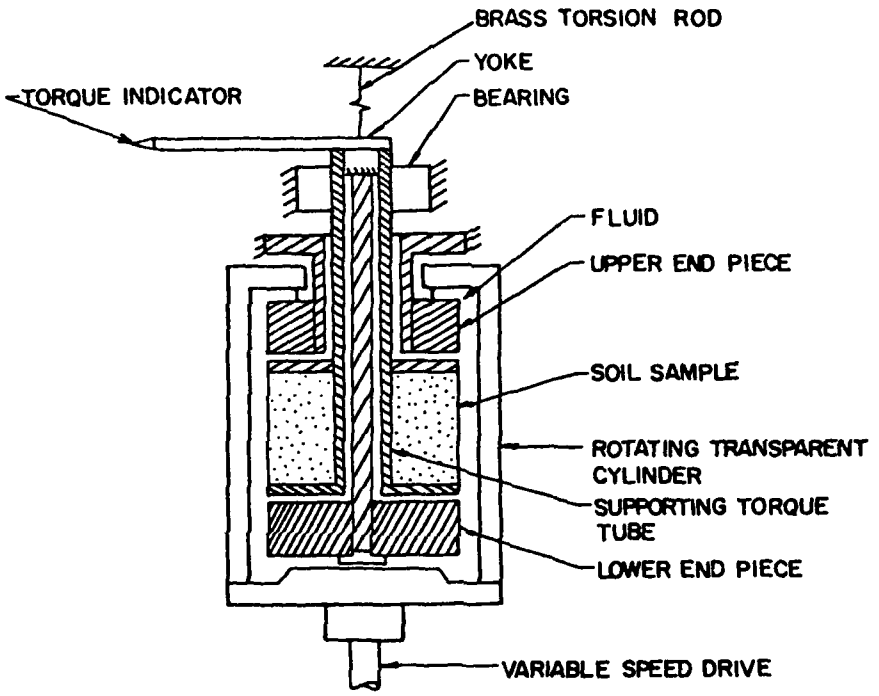

Figure 2. Cross-Sectional View of Rotating Cylinder Test Apparatus.

with water. An aluminum lid is placed on top of the cylinder to contain the water and to give lateral support to the vertical rod supporting the soil sample. An electrical tachometer is used with a voltmeter to measure RPM's of the outer cylinder. A curved metal surface with markings on its inside face is positioned in front of the rotating cylinder to measure deflections. A plastic dummy soil sample is used for calibration. The soil sample is held in place on the vertical shaft by washers which protect the top and bottom horizontal surfaces of the sample from erosion. A .020" piano wire, 3.1 inches long, is clamped to the upper end of the shaft by a gripping device. The vertical shaft holding the soil sample is nearly freely suspended from the piano wire.

45. When a soil sample is in the rotating cylinder, and the outside cylinder is turning, shear stress is imparted to the water contained by the cylinder. The water imparts shear stress to the soil sample. As the sample begins to turn, its suspending wire resists the shear stress in torque.

46. As the sample turns, a mirror mounted on the gripping device turns also. A strong light source (slide projector) projects light onto the mirror. The mirror reflects light onto the curved metal surface. As the mirror turns, the image of the suspending wire cast on the curved metal surface is displaced.

47. The apparatus has been calibrated so that a given deflection, as measured on the curved surface by the movement of the reflected projector light and wire shadow, can be converted directly to shear stress if the sample area is known. What is actually being measured by the movement of the reflected projector light on the curved surface is the total sum of the tangential forces on the soil sample surface.

48. During erosion tests the shear stress on the sample wall is measured directly from deflections of the wire image cast on the curved metal surface, provided the sample height and width are known. Generally the sample width does not vary substantially from its initial diameter of three inches during the erosion of soil particles.

Calibration of Rotating Cylinder

49. Measured angular deflections reflecting the light image from the rotating cylinder's suspending assembly were calibrated using known forces.

A three-inch diameter plastic dummy sample is suspended in place of a real soil sample. The suspending apparatus is raised from its usual position on top of the rotating cylinder so that a thread may be wrapped around the plastic dummy sample and extended horizontally. A meter stick is suspended horizontally some 70 cm over the rotating cylinder, directly overhead and parallel to the horizontal thread extending from the dummy sample. A 100 gm weight is suspended by a light thread from a paper clip bent so that it slides along the meter stick. The horizontal thread from the dummy sample is tied with a slip knot to the vertical thread hanging from the meter stick and supporting the 100 gm weight.

50. As the paper clip is moved along the meter stick away from the dummy surface, the thread attached to it makes an angle with the vertical, and a horizontal force is imparted to the dummy surface. The slip knot attaching the horizontal thread to the vertical thread is moved so that the horizontal thread remains horizontal.

51. The calibration procedure, as given in Appendix D reduces to simple statics. For a given movement **x** of the paper clip, measured directly from the meter stick, the corresponding horizontal force on the dummy sample is calculated by:

$$\frac{x}{y} = \frac{F}{Wt}$$

$$y = 66.8 \text{ cm} = \text{constant}$$

$$Wt = 100 \text{ gm } (980) \text{ dynes/gm} = 98000 \text{ dynes}$$

52. The distance x is corrected for horizontal movement of the vertical portion of the thread supporting the 100 gm weight, resulting from twist of the supporting wire, by using a thread-supported plumb bob hanging from the meter stick.

53. As the paper clip supporting the 100 gm weight is moved to different positions along the meter stick, different horizontal forces may be calculated, corresponding with different measured positions of the reflected wire shadow on the curved surface. Positions of the reflected wire shadow

were marked on engineering graph paper taped to the curved metal surface. Positions between the measured marks were also marked so that force readings other than those measured could be easily interpolated. Twenty-one deflection measurements were taken for horizontal forces ranging from 0 to ≅ 25,000 dynes. The measurements were repeated and averaged between positions marked when horizontal forces were increased and decreased.

54. It was found that for equal movements of the weight-supporting paper clip along the meter stick, the distances between the corresponding reflected wire shadow marks on the curved surface were about equal. These distances could be approximated for the calibration as 1270 dynes/measured division. This approximation was repeatable within about 2% of the measured force (except at very low deflections where error was 7%). The distance on the curved surface between any two adjacent measured reflected wire shadow images was about 3.64 divisions on the engineering paper taped to the curved surface. Therefore, extrapolations were made beyond the calibrated 25,000 dyne force range during tests using 1270 dynes/3.64 divisions of engineering paper as means for calculating extrapolated forces.

55. The rotating cylinder was checked before, during, and after the test series. Calibration changes were small and it was possible, by adjusting the length of the supporting wire, to correct any drift in calibration. Included in Appendix D is a copy of a calibration check.

56. During the latter part of the testing series the rotating cylinder apparatus was adjusted by replacing the suspending wire with a .031 inch diameter piano wire 3.775 inches long, more than doubling the range of measurable shear stress that could be applied to the sample.

Testing Erosion Samples In Rotating Cylinder

Sample preparation

57. Paste. A soil paste is prepared by crushing and mixing a given soil with distilled water until two criteria are met:

a. Soil falls cleanly off motionless vertical metal (spatula) face.
b. Soil just begins to flow as mixing tub is substantially tipped.

In addition to these two criteria, the soil must be uniformly mixed, with no chunks of soil remaining. This is a problem with highly clayey soils. Therefore, to insure complete mixing with the distilled water, the soil paste is allowed to set overnight. The paste is then remixed. If the paste produces free water after having set overnight, it has been mixed with too much water. An ideal paste will be just at the point of producing free water. However, highly clayey soils will often absorb overnight what had at first appeared as free water, and more distilled water must be added the next day. Thus, a properly produced paste will produce a very small quantity of free water after having set overnight.

58. Slurry. Once a soil paste has been prepared, a salt solution is mixed with it until its consistency is that of a slurry, or liquid. The consistency of the slurry should be such that it will pour easily into consolidation molds. However, too much salt solution may cause the slurry to be so liquid as to clog the consolidation drainage apparatus.

59. The salt solution is prepared by adding pre-determined amounts of given concentrations of calcium, magnesium, potassium, and sodium solutions to distilled water. The salt solution matches as nearly as possible the chemical composition of fluid extracted from the soil paste, with respect to SAR, total dissolved salt concentration, and the four above cations.

60. Consolidation. A 3/4" diameter vertical rod is inserted into the mold before the slurry is added. This rod will support the sample during testing. Filter paper is wrapped around the rod, wetted with the prepared salt solution, and is of a sufficient length to connect top and bottom porous stones so that drainage during consolidation is facilitated. The slurry is slowly poured into a greased consolidation mold, the mold being tapped to release any trapped air bubbles. The consolidation mold is double-drained through porous stones, with the squeezings being collected from a drainage line at the base.

61. Consolidating weights are added incrementally until the sample enters secondary consolidation at .75 kgm/cm^2. The sample is removed and its squeezings are saved for future chemical analysis and correlation with paste chemical analysis.

62. Trimming, measuring, and weighing. The sample is extruded from the mold and trimmed to about 3.55" length. The trimmings are saved for water content determinations to make sure that the several samples of the same soil are consolidated to the same degree. Once trimmed to approximate length, the sample is measured for length and width with calipers and weighed so that density determinations can be made. The sample, supported top and bottom by washers and by the 3/4" rod running through its vertical axis, is trimmed with a wire saw to remove the outer ≈ .005" of disturbed and grease-contaminated soil.

Testing

63. Initial erosion and soaking. The rotating cylinder apparatus is filled with specified eroding fluid and the trimmed sample is placed in the apparatus, immersed in the fluid. The sample is then initially eroded, both to remove any disturbed outer soil and to create a smooth, natural eroded surface for the test. The approximate τ_c, at the onset of erosion as observed through the cylinder walls, is noted.

64. When enough erosion has occurred to considerably cloud the eroding fluid, the rotating cylinder is stopped, and the sample is allowed to remain immersed in the cylinder, soaking 2 to 3 hours in the eroding fluid. Soaking allows the sample to come into adjustment with its eroding fluid just as soil would in the natural or field condition.

65. Four-minute soaking intervals. Directly before each test begins the sample is weighed, soaked four minutes, and re-weighed. During the test, the time that the sample is immersed during one erosion test point is about four minutes. The four-minute soak prior to testing allows some estimation of water uptake, or expulsion, during a test point and corrections can be made accordingly to isolate the weight change effects from erosion. During the course of the test, other four-minute soaking intervals are performed and recorded as the influence of static immersion of the sample in its eroding fluid on sample weight change is different during the course of the test. Usually, a four-minute soaking interval is also taken after the first four test points and again after all testing is complete. An estimation

of sample weight change due to soaking over the whole course of the test is interpolated and used to correct the test data.

66. Test point procedure. An erosion test consists of a number of erosion measurements, or test points. During each test point, the rotating cylinder is set to turn at a given speed for a period of two minutes. During the two minute erosion period, two shear force readings are taken, directly measuring the total force imparted to the sample surface by the rotating fluid. The average of these two readings is taken for use in calculations. The first reading is taken at 50 seconds and the second at 90 seconds in order to account for any change or drift in shear force due to hydrodynamic changes or changes in the sample surface.

67. The sample is weighed before and after each test point. After a test point, the rod and washers are dried with paper tissues in a consistent manner. The sample is then weighed as promptly as possible. The time allowed between test points should be brief, as the sample air-dries rapidly and may behave differently in the next test point due to changed erosion or water uptake characteristics resulting from too much air-drying. The sample is also measured for length and diameter after each checkpoint so that correct surface areas are obtained for calculation of shear stresses.

68. During the course of the test, preliminary measured values of weight-loss vs shear stress are plotted. These values correspond roughly to the trend of values of erosion rate vs shear stress obtained later. It is on the basis of the preliminary plotting that rotating cylinder speeds are selected during the test, and that the decision is reached to end the test.

69. After the test is completed, a chunk of soil is removed from the sample for determining the water content.

Modifications to soaking and test point procedures

70. During a final series of rotating cylinder tests (repeat series), soil samples were soaked about three hours in their respective pore fluids. After having fully rebounded, the soil samples were soaked about thirty minutes in their respective eroding fluids. It was felt that soaking the samples in their own pore fluid while they rebounded more nearly simulated in situ soil conditions than the method described in paragraphs 60-61.

71. Also in the final series of rotating cylinder tests, the soil samples were eroded four or five times, consecutively, for each shear stress level applied in the test. The duration of each test point remained two minutes. The purpose of eroding each sample many times at the same shear stress was to allow the samples to come to a steady state erosion rate, in recognition of the fact that the initial erosion rate of some soils that are suddenly subjected to shear stress may change after a few moments.

Calculations

72. For each test point in an erosion test, values of erosion rate and shear stress are calculated from the measured data. The shear stress is calculated by dividing the measured averaged shear force by the surface area measured for the particular test point. The surface area is calculated by the product of the measured diameter (estimated average diameter when necessary) and the measured sample length, including washers. The end surfaces are neglected since the space between washers and cylinder apparatus is small ($\simeq$ 1/16") and the exposed surfaces of the washers are very smooth. End effects on rotational force transferred to the sample are assumed negligible.

73. The erosion rate is calculated from the values of erosion surface area, weight change corrected for water uptake, and time duration of the test point. The erosion surface area is the product of measured diameter and length (length not including washers). The measured weight change is corrected for water uptake as follows: the weight change from a four-minute soaking period is plotted vs the test point number of the erosion test point following each soaking period. The soaking period weight change before the test is paired with the number one. The soaking period weight change before test five is paired with the number 5. The soaking period weight change at the end of the test is paired with the number n + 1, for n number of test points during the test. Weight gain is negative, and weight loss is positive. For each test point the measured weight change is corrected with the formula:

$$\Delta Wt_{measured} = \Delta Wt_{erosion} + \Delta Wt_{soaking}$$

$$\Delta Wt_{erosion} = \Delta Wt_{measured} - \Delta Wt_{soaking}$$

The values of soaking weight change for test points not directly paired with soaking intervals are estimated from a soaking weight change vs test point number plot.

74. The erosion rate is calculated by:

$$\dot{\epsilon} = \frac{\Delta Wt_{erosion}}{(Area)(Time)}$$

and has the units: $gm/(cm^2 - min)$.

75. Modification to calculations. For rotating cylinder tests using multiple test points per shear stress, erosion rate was determined by plotting cumulative time vs cumulative actual soil weight loss and taking the slope of the best fit through the points. Often, the line determining the best fit does not go through the origin (it should not if there is a change in erosion rate). When there are two groupings of points, the slope is determined by the best fit of a line passing through the group of points describing erosion rate during the final test points taken at a given shear stress.

Eroding Fluid Range

76. Tests on a given soil are performed for a variety of eroding fluid salt concentrations, including distilled water, so that field behavior may be estimated for all likely possibilities.

77. Recommended Procedures and Calculations. It is recommended that samples be soaked and tested in accordance with paragraphs 69-70 and calculations be done in accordance with paragraph 74. These methods more accurately follow in situ conditions of erosion and previous work done by Alizadeh and Kandiah (6,7).

Critical Shear Stress, τ_c, And Slope Of Erosion Line, s Determination For Flume and Rotating Cylinder Tests

78. Corrected values of erosion rate vs shear stress are plotted to determine critical shear stress τ_c and the slope of the erosion line (rate of change of erosion rate with respect to shear stress).

79. Often, $\dot{\epsilon}$ vs shear stress plots is a line having three distinct slopes, the first gradual, the second steep, and the third gradual. It is the extrapolation of the second, steep portion that yields τ_c as the shear stress abscissa is crossed. The slope of this portion of the plot is considered the slope of the erosion line, s. When the line plotted as $\dot{\epsilon}$ vs shear stress yields only steep, then gradual slopes, the steep section is taken for determination of τ_c and the slope of the erosion line. If the line determined by $\dot{\epsilon}$ vs shear stress has only one slope, it is used to determine τ_c and the slope of the erosion line, unless there is too much scatter or the slope of the line is very gradual. In the latter instances τ_c and/or the slope of erosion line is doubtful.

PART III: PRESENTATION OF DATA AND DISCUSSION OF RESULTS

Presentation of Data

80. The data presented in this report consist of:

a. Erosion rate vs shear stress plots for all remolded and undisturbed erosion tests. These plots are in appendices A, B, C, and F. In addition to plotting the results of each individual test on a separate graph, the results of different erosion tests performed on the same soil are plotted on the same graph. This allows comparison of effects of three different eroding fluid salt concentrations on the erodibility of a particular remolded soil, and also shows effects of remolding on the erodibility of a particular soil.

b. Tables 1 through 9 summarize information about the soils chosen for erosion tests, including the results of all tests performed to characterize these soils. Tables 1 through 4 in Appendix H summarize data obtained from soil characterization tests performed on soils initially selected for this study but not chosen for erosion tests.

c. Appendix D presenting an example of a rotating cylinder calibration.

d. Appendix E summarizing and describing the preliminary analysis and soil characterization tests done in the study.

e. SAR vs critical shear stress plots for soils covering a wide range of dielectric dispersion and pore fluid dissolved salt concentration. These relationships are based on results from Alizadeh's research (7) at UCD using artificial soils with 40% clay and are included in the discussion of results in the main body of the report. Also included in the discussion of results are plots correlating measured to predicted critical shear stress based on Alizadeh's work and a relationship between critical shear stress and rate of change of erosion rate.

f. Appendix G containing the plotted results of the final series of repeated remolded soil erosion tests done in the study and Tables 10-12 summarizing information about the soils tested in this series, including soil characterization, erosion test results and critical shear stress values predicted using correlations developed by Alizadeh. These tests were done by the methods described in paragraphs 69-70.

Discussion of Results

Effects of remolding on critical shear stress and rate of change of erosion rate

81. Figures F.1 through F.30 show the effect of remolding on τ_c and s for the soils tested in this study. Remolding usually decreased both τ_c and s. For soils showing these effects, erosion may be more pronounced for remolded soils at low shear stress, but still more pronounced for undisturbed soils at higher shear stress.

82. Figure 3 shows a predictive chart, developed by Alizadeh (7) and revised by Heinzen (9), designed to predict soil τ_c, given soil SAR, $\Delta\varepsilon_o$ and total salt concentration. The chart was developed using various artificial soil mixtures and distilled water as eroding fluid (Figures 4-7). Alizadeh's chart in Figure 3 was used to predict the critical shear stress of the undisturbed soils analyzed in this study. Predicted and measured values are plotted in Figure 8 for 14 soils that came reasonably close to a one-to-one relationship. For the 14 plotted soils and the remaining unplotted soils, Alizadeh's chart usually yielded a predicted value of τ_c that was less than the measured value. Figure 9 also shows Alizadeh's chart yielded predicted values of τ_c which were less than measured values of τ_c for remolded soils soaked in their pore fluids. The remolded soils tested, after being soaked in their eroding fluids, yielded predicted values of τ_c which were greater than measured values of τ_c, but soils tested in this manner may not be indicative of real soil behavior.

83. The effects of storage in steel containers may have served to increase the τ_c values of many undisturbed soils tested. Fe++ ions from the steel containers may have diffused through the soil during the prolonged storage period and considerably increased the soil's resistance to erosion. Any such diffusion of Fe++ ions would not have been detected in our measurements since chemical analysis of pore fluid was done from soil pastes prepared from bagged soil samples. The following tabulation summarizes the relationships between number of soils stored in steel containers and success in predicting τ_c.

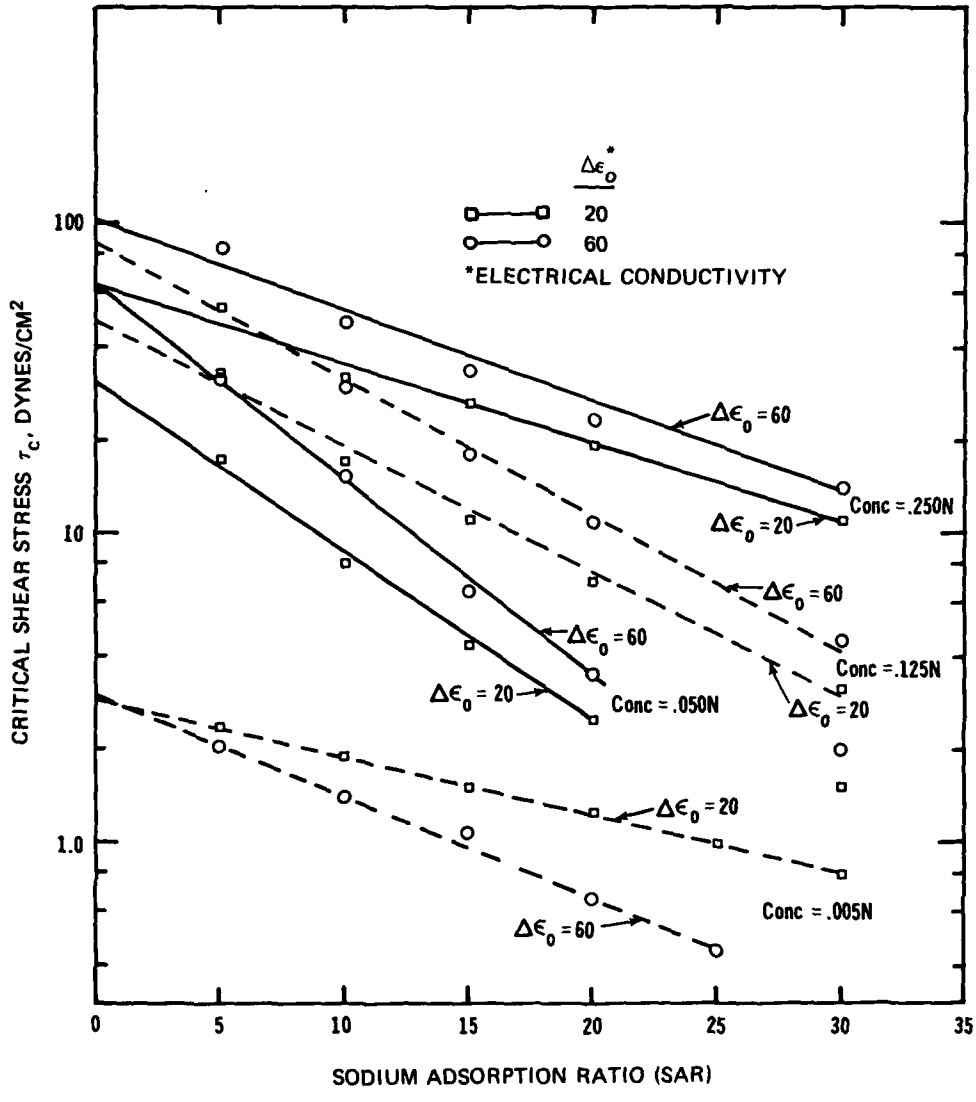

Figure 3. Critical Shear Stress τ_c vs SAR for Different Soil Salt Concentrations and Different Dielectric Dispersion $\Delta\varepsilon_o$ Values.

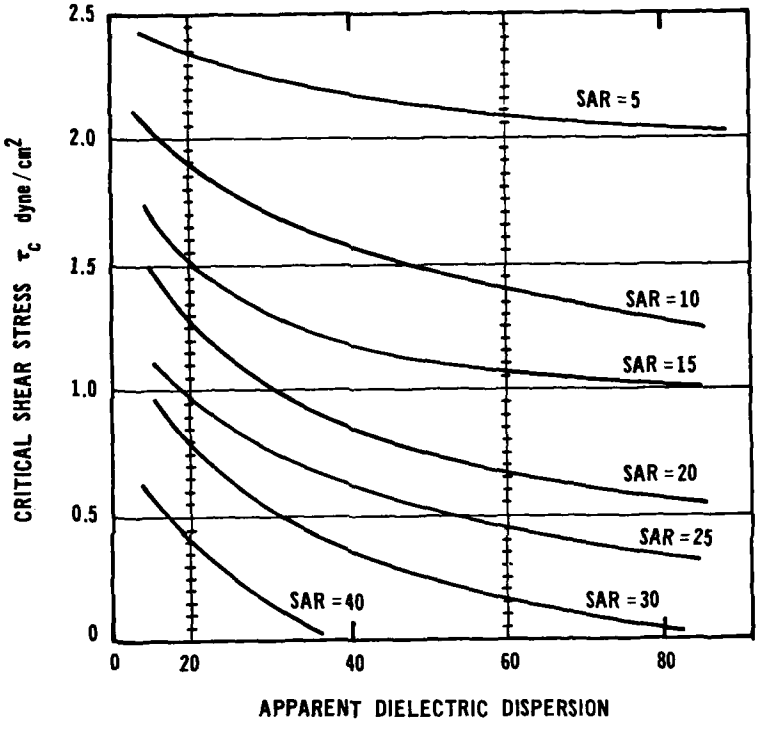

Figure 4. Relationship Between Critical Shear Stress and Dielectric Dispersion as a Function of SAR. Pore Fluid Concentration 0.005 N. (After Alizadeh (7))

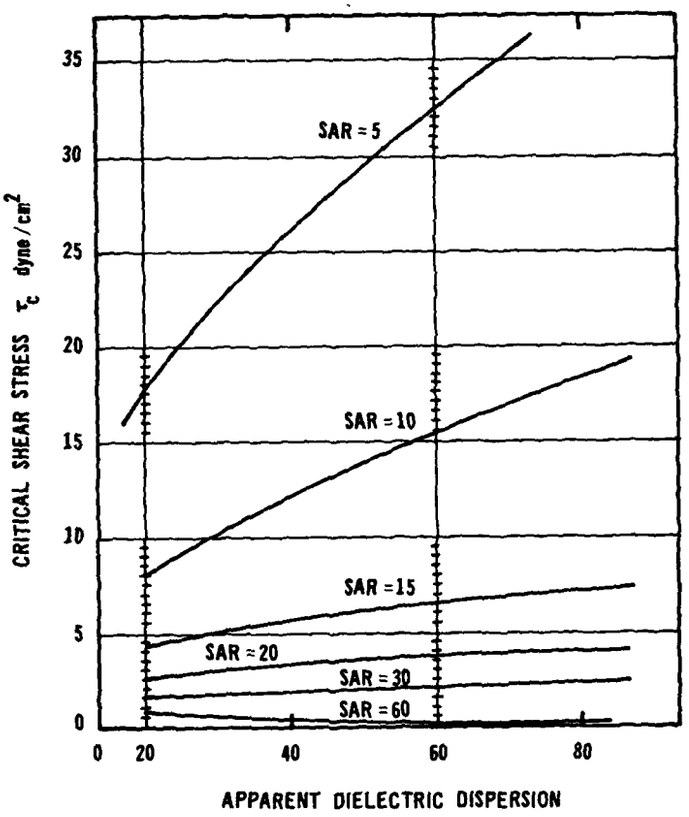

Figure 5. Relationship Between Critical Shear Stress and Dielectric Dispersion as a Function of SAR. Pore Fluid Concentration 0.050N. (After Alizadeh (7))

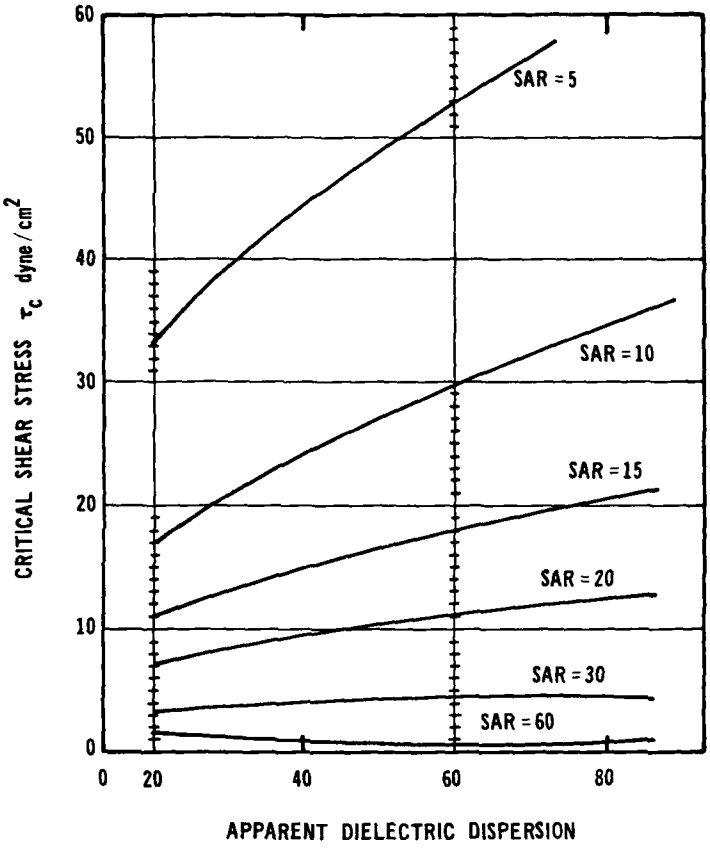

Figure 6. Relationship Between Critical Shear Stress and Dielectric Dispersion as a Function of SAR. Pore Fluid Concentration 0.125N. (After Alizadeh (7))

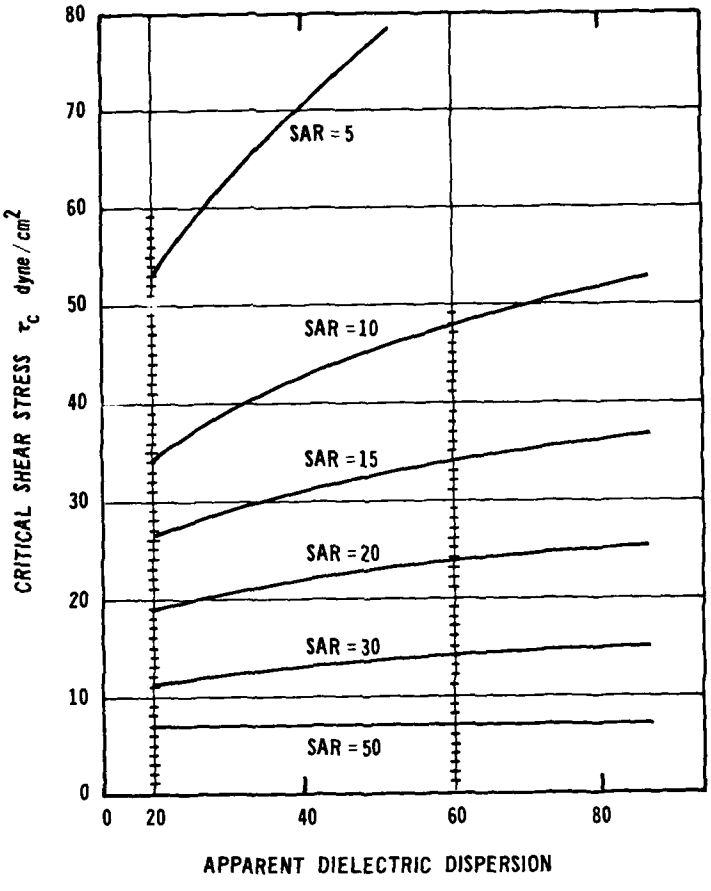

Figure 7. Relationship Between Critical Shear Stress and Dielectric Dispersion as a Function of SAR. Pore Fluid Concentration 0.250N. (After Alizadeh (7))

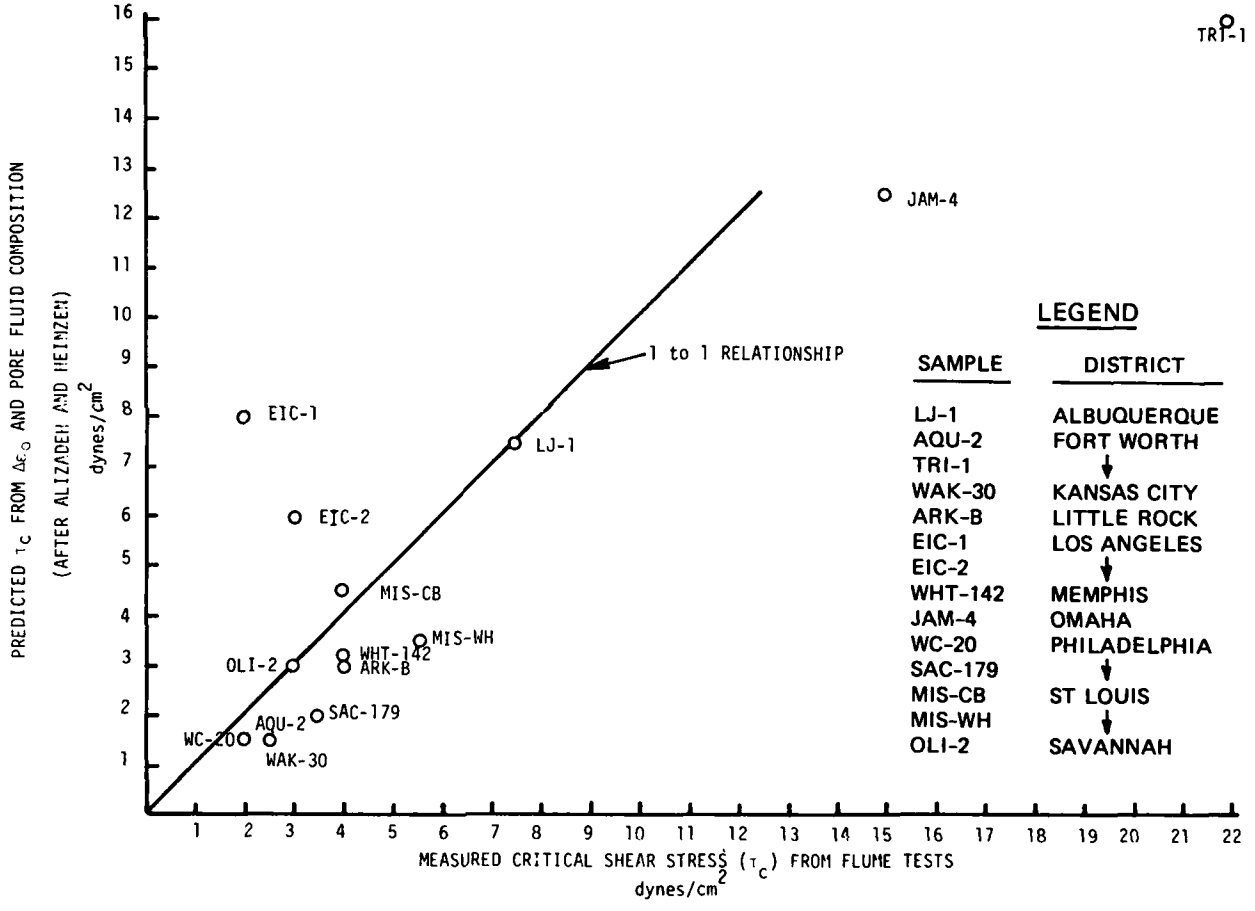

Figure 8. Predicted Critical Shear Stress (τ_c) from Dielectric Dispersion ($\Delta\varepsilon_o$) Values and Pore Fluid Composition vs Measured Critical Shear Stress for Undisturbed Soils Tested in Flume with Distilled Water Eroding Fluid.

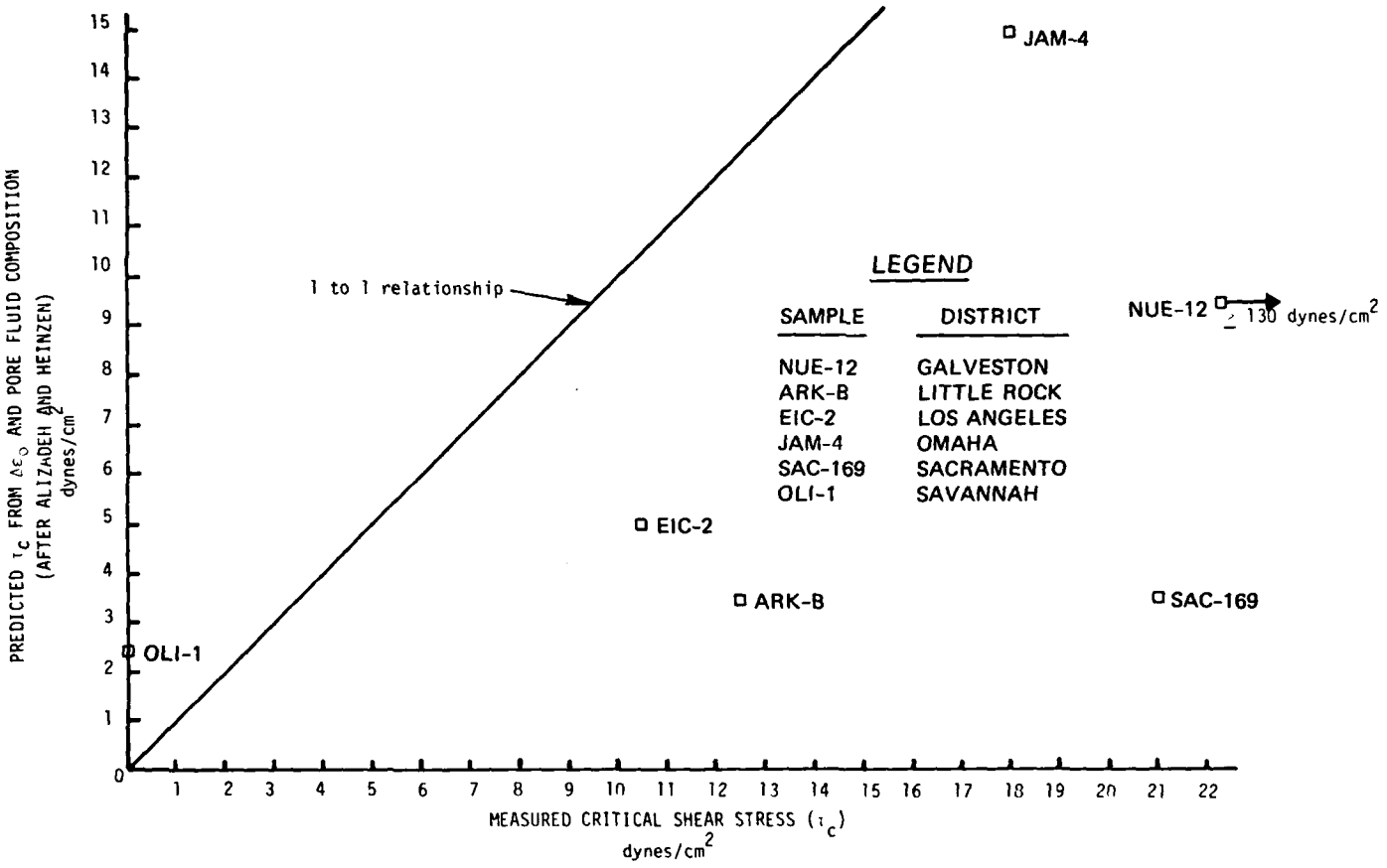

Figure 9. Predicted Critical Shear Stress τ_c from Dielectric Dispersion ($\Delta\varepsilon_o$) Values and Pore Fluid Composition vs Measured Critical Shear Stress (after Alizadeh (7) and Heinzen (9)) for Remolded Samples Soaked in Pore Fluid and Tested in Rotating Cylinder with Distilled Water as Eroding Fluid.

Possible Influence of Steel Containers on Erodibility

Number of Soils in Steel Containers	
τ_c Predicted Underestimated τ_c Measured	τ_c Predicted Within 3 dynes/cm^2 of τ_c Measured
12	7

Number of Soils Not in Steel Containers		
τ_c Predicted Underestimated τ_c Measured	τ_c Predicted Within 3 dynes/cm^2 of τ_c Measured	τ_c Predicted Overestimated τ_c Measured
3	7	1

Effects of eroding fluid salt concentration on erosion

84. Figures B.1 through B.27 show the effects of increasing salt concentration in the eroding fluid of remolded samples. Usually, as the salt concentration of eroding fluid increases the critical shear stress of a soil increases and the rate of change of erosion rate decreases, i.e. the soil becomes more resistant to erosion.

85. The increase in erosion resistance is accounted for by the decrease of osmotic pressure in the very outer layers of the soil sample that occurs with the decrease in the salt concentration gradients between the eroding fluid and sample fluid. As the salt concentration of the eroding fluid increases, it more nearly approaches the higher salt concentration of the sample pore fluid.

Effect of soaking soil sample in pore fluid

86. Remolded samples soaked in their eroding fluids tended to yield τ_c values much lower than those predicted by Alizadeh's chart. The remolded samples soaked in their pore fluids gave high τ_c values and lower s values. The important factor was soil rebound after removal of compressive load and extrusion from the mold. During the initial soaking period the sample experienced rebound and would necessarily draw soaking fluid into its outer layers. As eroding fluid generally had much lower salt concentration than the pore fluid, soaking in eroding fluid effectively diluted the pore fluid in the outer layers of soil and weakened the sample. It is recommended to soak remolded samples in pore fluid during their rebounding period, as the sample pore fluid would then remain unchanged and the soil sample would more nearly represent in situ behavior.

Relationship between critical shear stress τ_c and rate of change of erosion rate s

87. Figures 10 and 11, respectively, show the general relationship between τ_c and s for undisturbed samples and remolded samples. In both figures the trend is for soils exhibiting a low τ_c to have a high s and for soils having a high τ_c to have a low s value. If information on either τ_c or s is known, a qualitative prediction about τ_c (if s is known) or s (if τ_c is known) may be made outside the transition regions of the curves shown on the figures. These figures were prepared for eroding fluid of distilled water only.

Conclusions

88. Remolding the soil generally decreased both the critical shear stress and the rate of change of erosion rate.

89. The salt concentration of the eroding fluid significantly influenced the erosion of remolded soil samples. Usually, as the salt concentration of the river (eroding) water decreased, the critical shear stress decreased and the rate of change of erosion rate increased.

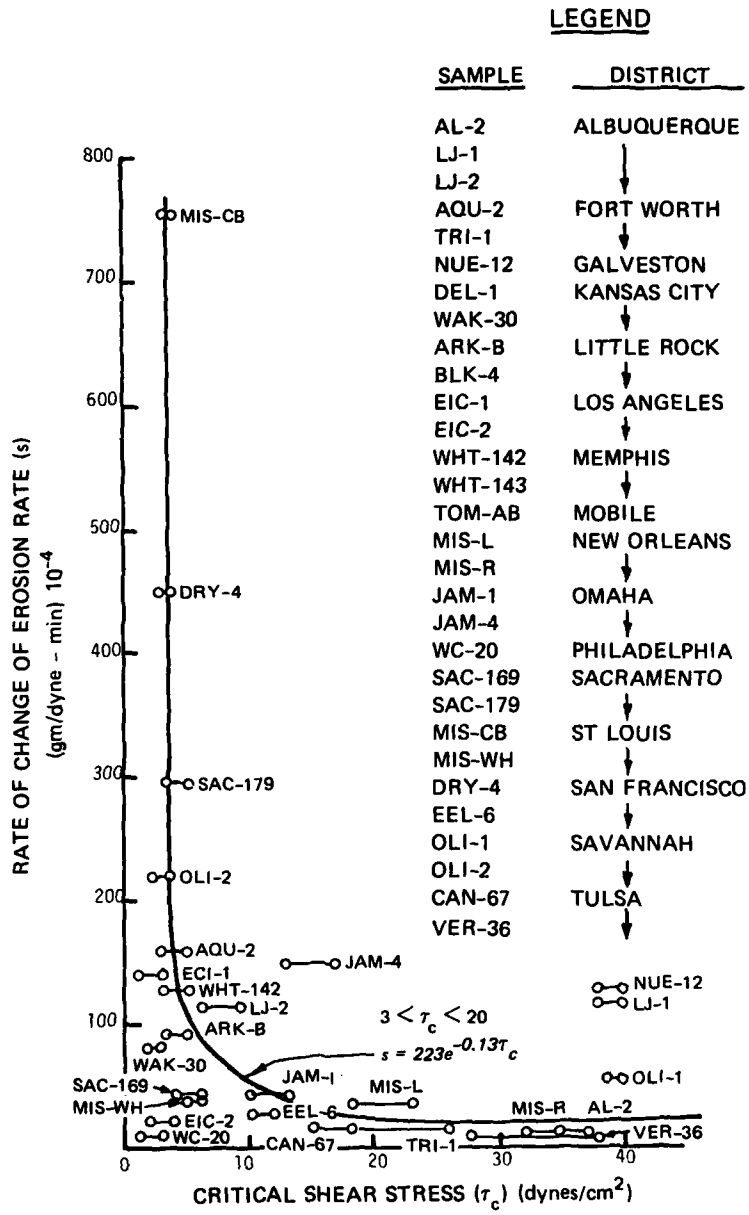

Figure 10. Rate of Change of Erosion Rate s vs Critical Shear Stress τ_c for Undisturbed Soils tested in Flume Using Distilled Water as Eroding Fluid.

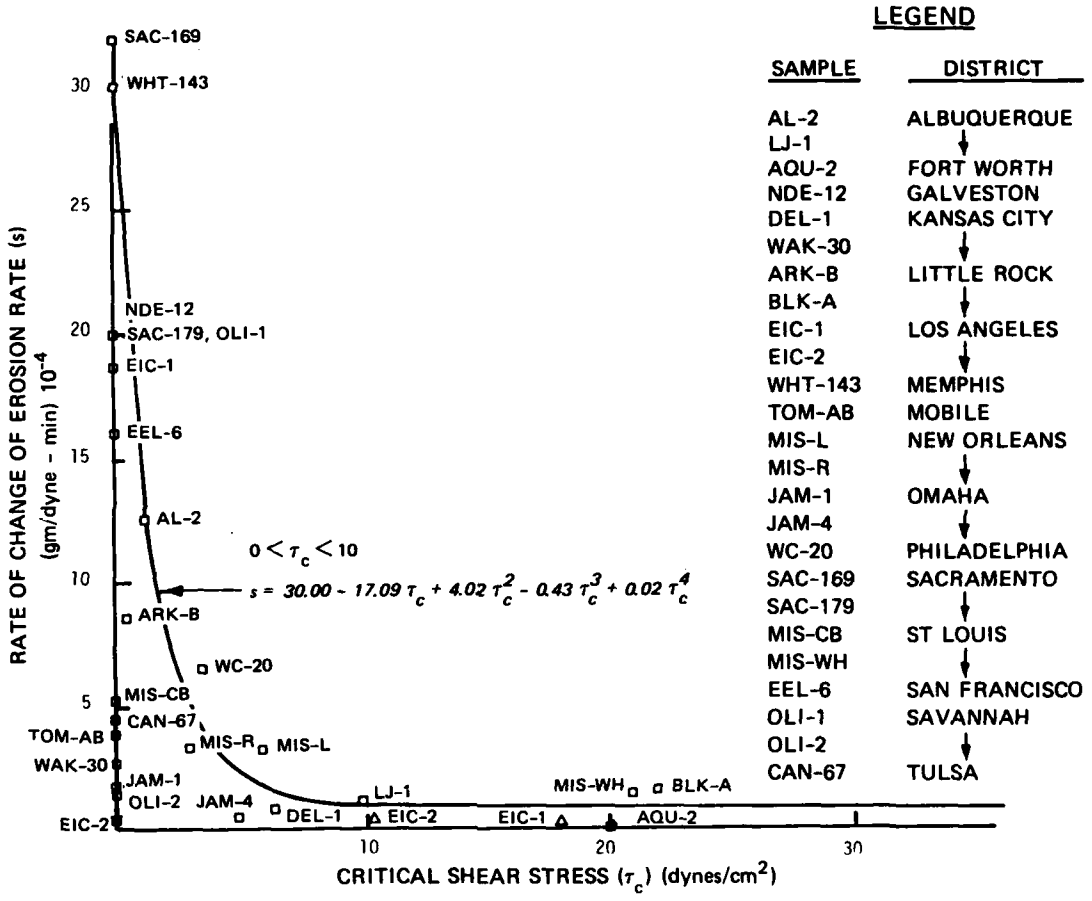

Figure 11. Rate of Chance of Erosion Rate s vs Critical Shear Stress τ_c for Remolded Samples Tested in Rotating Cylinder Using Distilled Water Eroding Fluid.

90. The results of this study did not yield a quantitative method to predict critical shear and/or rate of erosion for undisturbed natural soils. However, it was shown that a previously developed chart for remolded soils (Figure 3) gave a predicted critical shear stress for undisturbed soils which was generally less than the measured value using distilled water as the eroding fluid. Since the critical shear stress usually increases as the salt concentration of the eroding fluid increases, Figure 3 should give a reasonable estimate of the critical shear stress for a natural undisturbed soil subject to hydraulic shear stress from river (eroding) water. Using the estimated critical shear stress, a predictive chart developed in this study (Figure 10) of the relationship between critical shear stress and rate of change of erosion rate for undisturbed soil, using distilled water as eroding fluid, can be used to estimate the rate of change of erosion rate for a natural undisturbed soil subjected to hydraulic shear stress from river (eroding) water. The estimated rate of change of erosion rate will represent an upper bound because as the salt concentration increases, from distilled water to river water concentration, the rate of erosion rate decreases.

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Table 1

Soil Sample Information

District	District Sample I.D.	Date Received	Location*	Soil Sample I.D.	Undisturbed Sample**	Erodibility Observed in the Field
San Francisco, CA	1A	10/14/77	Eel River RM 6	EEL-6	B	Erodible
San Francisco,	1B	10/14/77	Dry Creek RM 8	DRY-4	B	Non-erodible
Sacramento, CA	2A	10/4/77	Sacramento R. RM 169 top of bank	SAC-169	A	Erodible
Sacramento, CA	2B	10/4/77	Sacramento R. RM 179 top of bank	SAC-179	A	Less erodibility than SAC-169
Memphis, TN	3A	10/14/77	White R. RM 143 Depth: 11.0' to 13.5'	WHT-143	C	Non-erodible

(Continued)

* RM = River Mile

** A = 3 inch diameter steel shelby tube
B = Teflon coated 3 inch diameter steel shelby tube
C = 6 inch diameter steel shelby tube
D = Cut rectangular block of soil, waxed and boxed
E = Cylindrical core sample, waxed and protected in cardboard tubes

Table 1 (Continued)

District	District Sample I.D.	Date Received	Location*	Soil Sample I.D.	Undisturbed Sample **	Erodibility Observed in the Field
Memphis, TN	3B	10/14/77	White R. RM 142 Depth: 10'-14' 21'-23.5', 37'-41'	WHT-142	C	Erodible
Charleston, NC	4A	10/28/77	Roaring R. HWY 268 bridge at Roaring R. top of 15' high bank	ROA-A	D	Erodible
Charleston, NC	4B	10/28/77	Roaring R. Approx. 1 mile upstream of ROA-A 6 ft. from river edge	ROA-B	D	Erodible
Vicksburg, MS	5A	10/28/77	N. fork Tillatoba Cr.	TIL-A	A+D	——
Vicksburg, MS	5B	10/28/77	N. fork Tillatoba Cr.	TIL-B	A+D	——
Mobile, AL	6A	11/4/77	Tombigbee R. 100 yds. N. of HWY 78 bridge Depth: 1.0'-2.5'	TOM-FN	A	Erodible
Mobile, AL	6B	11/4/77	Tombigbee R. 0.8 mi. N.W. of HWY 45 bridge Depth: 0.5'-2.0'	TOM-AB	A	Non-erodible

(Continued)

Table 1 (Continued)

District	District Sample I.D.	Date Received	Location*	Soil Sample I.D.	Undisturbed Sample **	Erodibility Observed in the Field
St. Louis, MO	7A	11/16/77	Mississippi R. RM 498 on MO bank Depth: 8.0'-11.5'	MIS-CB	A	Non-erodible
St. Louis, MO	7B	11/16/77	Mississippi R. RM 536 on IL bank Depth: 8.0'-11.0'	MIS-WH	B	Non-erodible
New England Division	8A	11/23/77	Connecticut R. RM 237 Depth: 1.8'-3.1'	CON-237	D	——
New England Division	8B	11/23/77	Connecticut R. RM 254 Depth: 0.0'-1.9'	CON-254	D	——
Omaha, NB	9A	11/29/77	James R. HWY 50 bridge	JAM-1	D	Non-erodible
Omaha, NB	9B	11/29/77	Missouri R. RM 801	MIO-2	D	Erodible
Omaha, NB	9C	11/29/77	Missouri R. RM 796	MIO-3	D	Erodible
Omaha, NB	9D	11/29/77	James R. North Co. HWY bridge	JAM-4	D	Non-erodible
Kansas City, MO	10A	12/15/77	Delaware R. RM 181 Depth: 1.0'-3.0'	DEL-1	E	Erodible

(Continued)

Table 1 (Continued)

District	District Sample I.D.	Date Received	Location*	Soil Sample I.D.	Undisturbed Sample**	Erodibility Observed in the Field
Kansas City, MO	10B	12/15/77	Wakarusa R. RM 30.4 Depth: 1.0'-3.0'	WAK-30	E	Non-erodible
Los Angeles, CA	11A	12/20/77	El Modeno/ Irvine Channel 200 ft. N. of Vanderlip Ave. near Tustin, CA Depth: 3.5'-4.5'	EIC-1	D	Non-erodible
Los Angeles, CA	11B	12/20/77	El Modeno/ Irvine Channel 1500 ft. N.W. of Myford Rd. and Bryan Ave. intersection near Tustin, CA Depth: 3.5'-4.5'	EIC-2	D	Erodible
Little Rock, AR	12A	12/5/78	Black R. 50 ft. upstream of Corning, AR bridge	BLK-A	A	Non-erodible
Little Rock, AR	12B	1/5/78	Arkansas R. 500 ft. upstream of Conway, AR bridge	ARK-B		Erodible
Fort Worth, TX	13A	1/12/78	Trinity R., Site1 Depth: 0.0'-3.0'	TRI-1	A	——

(Continued)

Table 1 (Continued)

District	District Sample I.D.	Date Received	Location*	Soil Sample I.D.	Undisturbed Sample **	Erodibility Observed in the Field
Fort Worth, TX	13B	1/12/78	Aquilla Cr., Site 2 Depth: 0.0'-3.0'	AQU-2	A	——
Tulsa, OK	14A	1/18/78	Verdigris R. RM 36.5	VER-36	A	Erodible
Tulsa, OK	14B	1/18/78	Caney R. RM 67.5	CAN-67	A	Non-erodible
Savannah, GA	15A	1/30/78	Savannah R. Olin Plant near Augusta, GA Depth: 17.5'-19.0'	OLI-1	A	——
Savannah, GA	15B	1/30/78	Savannah R. Olin Plant near Augusta, GA Depth: 12.0'-15.0'	OLI-2	A	——
Galveston, TX	16A	3/13/78	Trinity R. RM 78.0 Depth: 1.0'-3.0'	TRI-78	E	Erodible
Galveston, TX	16B	5/23/78	Nueces R. RM 12.0	NUE-12	E	Non-erodible

(Continued)

Table 1 (Continued)

District	District Sample I.D.	Date Received	Location*	Soil Sample I.D.	Undisturbed Sample **	Erodibility Observed in the Field
New Orleans, LA	17A	3/20/78	Mississippi R. Sta. 1608 + 00 500 ft. river side of left bank levee centerline Depth: 20.0'-29.0'	MIS-L	A	——
New Orleans, LA	17B	3/20/78	Mississippi R. Sta. 5608 + 00 300 ft. river side of right bank levee centerline Depth: 20.0'-29.0'	MIS-R	A	——
Albuquerque, NM	18A	4/4/78	Arkansas R. 5 mi. E. of La Junta Colo. on N. bank Depth: 0.0'-1.0'	LJ-1	A	Non-erodible
Albuquerque, NM	18B	4/4/78	Arkansas R. 4.5 mi. E. of La Junta, Colo. on S. bank Depth: 0.0'-1.0'	LJ-2	A	Erodible
Albuquerque, NM	18C	4/4/78	Rio Grande R. 1000 ft. S. of Rio Bravo blvd. bridge Albuquerque, NM on E. bank Depth: 0.0'-1.0'	AL-1	D	Erodible

(Continued)

Table 1 (Concluded)

District	Distirct Sample I.D.	Date Received	Location*	Soil Sample I.D.	Indisturtbed Sample**	Erodibility observed in the Field
Albuquerque, NM	18D	4/4/78	Rio Grande R. 1 mi. S. of Rio Bravo Blvd. bridge, Albuquerque, NM on W. bank Depth: 0.0'-1.0'	AL-2	A	Non-erodible
Philadelphia, PA	19A	4/7/78	White Clay Dr. RM 20[59] Depth: 1.0'-3.0'	WC-20	D	Erodible
Philadelphia, PA	19B	4/7/78	White Clay Dr. RM 19[69] Depth: 1.0'-1.83'	WC-19	D	Non-erodible

Table 2

Properties of River Water Tested

Soil Location and I.D.	pH*	meq/l				Total Salts meq/l	SAR
		Na	K	Mg	Ca		
Albuquerque District AL-2	7.8	1.6	.12	1.05	1.05	3.8	1.6
Albuquerque District LJ-1	8.2	12.3	.27	5.75	5.75	24.1	5.1
Albuquerque District LJ-2	8.2	12.2	.25	5.25	5.25	23.0	5.3
Fort Worth District AQU-2	7.9	5.3	.11	2.65	2.65	10.7	3.3
Fort Worth District TRI-1	6.9	4.1	.33	1.15	1.15	6.7	3.8
Galveston District NUE-12	7.9	35.7	.65	6.0	6.0	48.4	14.6
Kansas City District DEL-1	7.6	.30	.14	1.35	1.35	3.1	.3
Kansas City District WAK-30	7.9	.60	.07	2.6	2.6	5.9	.4
Little Rock District ARK-8	7.6	0.75	0.06	0.6	0.6	2.0	1.0

(Continued)

* pH of actual eroding fluid not taken.

Table 2 (Continued)

Soil Location and I.D.	pH*	meq/l Na	K	Mg	Ca	Total Salts meq/l	SAR
Little Rock District BLK-A	7.5	0.05	0.05	0.55	0.55	1.2	0.1
Los Angeles District EIC-1	7.9	14.0	0.09	4.75	4.75	23.6	6.4
Los Angeles District EIC-2	7.9	14.0	0.09	4.75	4.75	23.6	6.4
Memphis District WHT-142	7.5	0.1	0.08	0.70	0.70	1.6	0.1
Memphis District WHT-143	7.5	0.1	0.07	0.35	0.35	0.9	0.2
Mobile District TOM-AB	7.0	0.2	0.07	0.20	0.20	0.67	0.5
New Orleans District MIS-L	8.1	0.78	0.08	1.0	1.0	2.86	0.8
New Orleans District MIS-R	8.2	0.77	0.08	1.1	1.1	3.05	0.7
Omaha District JAM-1	7.6	2.2	0.38	4.75	4.75	12.1	1.0
Omaha District JAM-4	7.9	2.6	0.38	5.0	5.0	13.0	1.2
Philadelphia District WC-20	6.7	0.33	0.14	0.47	0.47	1.41	0.5

(Continued)

Table 2 (Concluded)

Soil Location and I.D.	pH	meq/l Na	K	Mg	Ca	Total Salts meq/l	SAR
Sacramento District SAC-169	7.4	0.40	0.06	0.46	0.46	1.4	0.6
Sacramento District SAC-179	7.5	0.40	0.06	0.46	0.46	1.4	0.6
St. Louis District MIS-CB	7.6	0.7	0.14	1.35	1.35	3.5	0.6
St. Louis District MIS-WH	7.7	0.60	0.13	1.35	1.35	3.5	0.5
San Francisco District DRY-4	7.5	0.4	0.04	1.05	1.05	2.5	0.4
San Francisco District EEL-6	7.8	0.4	0.05	1.15	1.15	2.8	0.4
Savannah District OLI-1	6.9	0.22	0.05	0.07	0.07	0.4	0.9
Savannah District OLI-2	6.9	0.22	0.05	0.07	0.07	0.4	0.9
Tulsa District CAN-67	7.1	1.6	0.11	2.0	2.0	5.7	1.1
Tulsa District VER-36	6.8	0.74	0.18	1.15	1.15	3.2	0.7

Table 3

Classification of Soils Tested

Soil Location and I.D.	Liquid Limit	Plastic Limit	Plasticity Index	Finer Than .002 mm %	Specific Gravity of Solids	Unified Soil Classification
Albuquerque District AL-2	31.2	23.1	8.1	13	2.60	ML*
Albuquerque District LJ-1	30.0	21.0	9.0	22	2.66	CL
Albuquerque District LJ-2	22.1	22.1	0.0	13	2.67	ML
Fort Worth District AQU-2	41.1	14.5	26.6	40	2.67	CL
Fort Worth District TRI-1	29.8	15.5	14.3	25	2.61	CL
Galveston District NUE-12	75.0	25.3	49.7	53	2.63	CH
Kansas City District DEL-1	31.5	20.4	11.1	33	2.62	CL
Kansas City District WAK-30	36.8	20.3	16.5	30	2.67	CL
Little Rock District ARK-B	24.0	22.1	1.9	17	2.69	ML
Little Rock District BLK-A	20.3	17.1	3.2	17	2.66	ML

(Continued)

* On A-line

Table 3 (Continued)

Soil Location and I.D.	Liquid Limit	Plastic Limit	Plasticity Index	Finer Than .002 mm %	Specific Gravity of Solids	Unified Soil Classification
Los Angeles District EIC-1	42.8	19.1	23.7	30	2.69	CL
Los Angeles District EIC-2	24.0	13.0	11.0	25	2.67	CL
Memphis District WHT-142	56.0	19.9	36.1	42	2.70	CH
Memphis District WHT-143	33.8	17.7	16.1	36	2.66	CL
Mobile District TOM-AB	42.0	23.2	18.8	37	2.65	CL
New Orleans District MIS-L	53.1	21.8	31.3	46	2.64	CH
New Orleans District MIS-R	55.5	21.4	34.1	25	2.63	CH
Omaha District JAM-1	54.0	28.7	25.3	42	2.68	CH*
Omaha District JAM-4	54.0	25.0	29.0	40	2.62	CH
Philadelphia District WC-20	25.6	25.6	0.0	12	2.72	ML

(Continued)

* On A-line

Table 3 (Concluded)

Soil Location and I.D.	Liquid Limit	Plastic Limit	Plasticity Index	Finer Than .002 mm %	Specific Gravity of Solids	Unified Soil Classification
Sacramento District SAC-169	29.2	20.4	8.8	14	2.73	CL
Sacramento District SAC-179	29.2	20.6	8.6	12	2.71	CL
St. Louis District MIS-CB	27.8	21.0	6.8	18	2.71	CL-ML
St. Louis District MIS-WH	44.9	23.6	21.3	34	2.65	CL
San Francisco District DRY-4	24.5	24.5	0.0	5	2.71	ML
San Francisco District EEL-6	27.0	24.0	3.0	6	2.70	ML
Savannah District OLI-1	38.3	27.8	10.5	29	2.67	ML
Savannah District OLI-2	38.3	23.0	15.3	28	2.65	CL
Tulsa District CAN-67	32.4	18.1	14.3	29	2.66	CL
Tulsa District VER-36	33.0	17.5	15.5	30	2.68	CL

Table 4

Physical Properties of Soils Tested

Soil Location and I.D.	Organic Content %	Gypsum meq/100 gm Soil	Dispersion Ratio %	Slaking gm/15 min	Free Swell %	Dielectric Undisturbed	Dispersion Remolded
Albuquerque District AL-2	5.1	0.25	44	-	5.5	26	22
Albuquerque District LJ-1	7.0	4.39	35	0.062	3.3	21	30
Albuquerque District LJ-2	7.8	3.59	38	0.075	5.3	10	18
Fort Worth District AQU-2	11.0	0.01	18	0.007	3.0	32	35
Fort Worth District TRI-1	10.4	0.11	31	0.133	>10.0	12	15
Galveston District NUE-12	7.1	0.00	19	0.053	41.8	20	47
Kansas City District DEL-1	4.7	0.02	17	0.142	7.3	19	25
Kansas City District WAK-30	5.0	0.01	26	0.261	0.4	30	24
Little Rock District ARK-B	4.0	0.00	92	0.090	0.0	7	9
Little Rock District BLK-A	3.3	0.00	65	0.011	4.1	13	18

(Continued)

Table 4 (Continued)

Soil Location and I.D.	Organic Content %	Gypsum meq/100gm Soil	Dispersion Ratio %	Slaking gm/15 min	Free Swell %	Dielectric Undisturbed	Dispersion Remolded
Los Angeles District EIC-1	5.2	0.01	26	0.242	9.9	15	25
Los Angeles District EIC-2	4.2	0.00	38	0.035	6.0	19	18
Memphis District WHT-142	7.5	0.00	100	0.004	11.6	41	36
Memphis District WHT-143	5.6	0.00	17	0.408	5.8	23	17
Mobile District TOM-AB	5.8	0.00	16	-0.004	9.0	24	27
New Orleans District MIS-L	5.5	0.00	55	0.081	2.4	46	43
New Orleans District MIS-R	4.0	0.00	38	0.135	7.5	24	28
Omaha District JAM-1	8.6	0.00	25	0.095	9.2	25	33
Omaha District JAM-4	11.6	1.45	23	0.040	11.7	20	17
Philadelphia District WC-20	5.1	0.00	58	-	14.7	12	9

(Continued)

Table 4 (Concluded)

Soil Location and I.D.	Organic Content %	Gypsum meq/100 gm Soil	Dispersion Ratio %	Slaking gm/15 min	Free Swell %	Dielectric Undisturbed	Dispersion Remolded
Sacramento District SAC-169	5.5	0.00	52	-	4.2	16	22
Sacramento District SAC-179	5.7	0.01	35	-	3.4	20	25
St. Louis District MIS-CB	3.0	0.00	100	0.322	6.5	15	16
St. Louis District MIS-WH	9.1	0.79	24	-0.009	0.0	43	26
San Francisco District DRY-4	4.9	0.00	100	-	2.6	12	14
San Francisco District EEL-6	5.0	0.00	88	-	5.6	12	11
Savannah District OLI-1	5.1	0.00	47	0.018	3.3	13	14
Savannah District OLI-2	6.4	0.00	26	-0.005	8.1	14	10
Tulsa District CAN-67	5.7	0.00	27	-0.004	8.6	17	18
Tulsa District VER-36	6.2	0.00	53	0.034	2.9	25	25

Table 5

Chemical Properties of Soil Tested

Soil Location and I.D.	Soil Pore Water Paste meq/l pH	Na	K	Mg	Ca	Total Salts meq/l	SAR	Cation Exchange Capacity C.E.C. meq/100gm
Albuquerque District AL-2	8.0	16.5	0.72	7.25	7.25	32.5	6.1	13.6
Albuquerque District LJ-1	8.0	137.0	1.0	25.0	25.0	205.	21.7	11.3
Albuquerque District LJ-2	8.2	103.0	0.36	20.0	20.0	145.	23.1	7.3
Fort Worth District AQU-2	7.3	0.07	0.07	0.95	0.95	2.7	0.1	20.4
Fort Worth District TRI-1	6.8	1.2	0.29	10.0	10.0	34.0	0.4	11.6
Galveston District NUE-12	8.0	39.0	0.22	7.0	7.0	55.0	14.8	9.8
Kansas City District DEL-1	7.4	0.10	0.10	1.3	1.3	2.9	0.1	15.5
Kansas City District WAK-30	7.3	0.10	0.23	1.0	1.0	2.5	0.1	14.5
Little Rock District ARK-B	7.3	0.28	0.10	1.4	1.4	5.6	0.2	9.0
Little Rock District BLK-A	7.4	0.09	0.06	0.38	0.38	1.3	0.1	7.9

(Continued)

Table 5 (Continued)

Soil Location and I.D.	Soil Pore Water Paste meq/l pH	Na	K	Mg	Ca	Total Salts meq/l	SAR	Cation Exchange Capacity C.E.C. meq/100gm
Los Angeles District EIC-1	7.5	13.0	0.06	7.5	7.5	29.0	4.7	20.0
Los Angeles District EIC-2	7.6	3.2	0.04	2.7	2.7	9.6	1.9	12.1
Memphis District WHT-142	5.9	8.5	0.07	1.35	1.35	10.8	9.2	27.5
Memphis District WHT-143	5.3	0.1	0.05	1.35	1.35	2.2	0.1	10.3
Mobile District TOM-AB	5.9	0.1	0.03	0.65	0.65	1.7	0.1	20.3
New Orleans District MIS-L	7.9	0.53	0.05	1.2	1.2	2.95	0.5	26.1
New Orleans District MIS-R	8.0	1.25	0.08	1.7	1.7	4.7	0.9	18.8
Omaha District JAM-1	7.4	1.9	0.29	2.05	2.05	6.0	1.3	24.1
Omaha District JAM-4	7.5	1.6	0.16	8.0	8.0	28.0	0.6	22.9
Philadelphia District WC-20	7.0	0.15	0.20	0.925	0.925	2.4	0.2	7.6

(Continued)

Table 5 (Concluded)

Soil Location and I.D.	Soil Pore Water Paste meq/l pH	Na	K	Mg	Ca	Total Salts meq/l	SAR	Cation Exchange Capacity C.E.C. meq/100gm
Sacramento District SAC-169	6.7	0.30	0.05	0.8	0.8	2.2	0.3	20.0
Sacramento District SAC-179	6.6	0.50	0.04	1.25	1.25	3.8	0.4	13.3
St. Loius District MIS-CB	7.2	1.2	0.02	3.0	3.0	8.0	0.7	9.2
St. Loius District MIS-WH	7.2	0.5	0.21	2.5	2.5	6.1	0.3	17.5
San Francisco District DRY-4	6.6	0.09	0.07	0.5	0.5	1.5	0.1	11.3
San Francisco District EEL-6	6.4	0.40	0.06	1.3	1.3	3.7	0.4	8.5
Savannah District OLI-1	5.2	0.10	0.04	0.20	0.20	1.1	0.2	13.5
Savannah District OLI-2	5.0	0.63	0.10	1.15	1.15	4.8	0.6	16.0
Tulsa District CAN-67	7.4	0.54	0.17	1.1	1.1	4.0	0.5	13.9
Tulsa District VER-36	6.3	0.42	0.04	0.55	0.55	2.2	0.6	14.2

Table 6

Index Properties of Undisturbed Samples Tested Flume

Soil Location and I.D.	Initial Conditions					Conditions After Saturation*
	Wet Unit weight lb/cu ft	Moisture Content %	Dry Unit weight lb/cu ft	Void Ratio	Degree of Saturation %	Moisture Content %
Albuquerque District AL-2	107.6	24.1	86.7	.87	72.0	29.4
Albuquerque District LJ-1	105.1	33.0	79.1	1.10	79.8	36.4
Albuquerque District LJ-2	96.5	18.1	81.7	1.04	46.5	42.2
Fort Worth District AQU-2	113.2	18.0	95.9	.74	64.9	29.0
Fort Worth Distrtict TRI-1	88.9	8.8	81.7	.99	23.2	23.8
Galveston District NUE-12	123.4	21.5	101.6	.62	91.2	35.6
Kansas City District DEL-1	115.4	24.9	92.4	.77	84.7	31.9
Kansas City District WAK-30	108.5	24.1	87.4	.91	70.7	36.1

(Continued)

* Final degree of saturation cannot be determined since volume measurements after soaking were not taken.

Table 6 (Continued)

Soil Location and I.D.	Initial Conditions					Conditions After Saturation
	Wet Unit weight lb/cu ft	Moisture Content %	Dry Unit weight lb/cu ft	Void Ratio	Degree of Saturation %	Moisture Content %
Little Rock District ARK-B	112.9	17.6	96.0	.75	63.1	28.9
Little Rock District BLK-A	112.4	23.8	90.8	.83	76.3	50.7
Los Angeles District EIC-1	112.8	21.8	92.6	.81	72.4	38.2
Los Angeles District EIC-2	130.4	14.0	114.4	.46	81.3	23.3
Memphis District WHT-142	129.5	28.4	100.8	.67	114.4	30.4
Memphis District WHT-143	109.6	13.1	96.9	.71	49.1	32.2
Mobile District TOM-AB	113.5	27.8	88.8	.86	85.7	35.9
New Orleans District MIS-L	115.6	33.9	86.3	.91	98.3	41.0
New Orleans District MIS-R	113.6	34.8	84.3	.95	96.3	----

(Continued)

Table 6 (Continued)

Soil Location and I.D.	Initial Conditions					Conditions After Saturation
	Wet Unit weight lb/cu ft	Moisture Content %	Dry Unit weight lb/cu ft	Void Ratio	Degree of Saturation %	Moisture Content %
Omaha District JAM-1	100.6	30.0	77.4	1.16	69.3	46.5
Omaha District JAM-4	100.3	38.1	72.6	1.25	79.9	49.5
Philadelphia District WC-20	101.5	26.5	80.2	1.12	64.4	38.8
Sacramento District SAC-169	79.4	6.1	74.8	1.28	13.0	43.2
Sacramento District SAC-179	105.3	9.5	[illegible]	.76	33.9	44.3
St. Loius District MIS-CB	121.4	23.2	98.5	.72	87.3	35.0
St. Loius District MIS-WH	110.0	35.6	81.1	1.04	90.7	37.8

(Continued)

Table 6 (Concluded)

Soil Location and I.D.	Initial Conditions					Conditions After Saturation
	Wet Unit weight lb/cu ft	Moisture Content %	Dry Unit weight lb/cu ft	Void Ratio	Degree of Saturation %	Moisture Content %
San Francisco District DRY-4	90.2	13.3	79.6	1.12	32.2	33.9
San Francisco District EEL-6	92.1	7.9	85.4	.97	22.0	30.6
Savannah District OLI-1	104.5	19.5	87.4	.91	57.2	30.0
Savannah District OLI-2	107.7	23.0	87.5	.89	68.5	43.0
Tulsa District CAN-67	100.4	24.7	80.5	1.06	62.0	30.4
Tulsa District VER-36	106.1	25.8	84.4	.98	70.6	31.7

Table 7

Results of Flume Tests on Saturated Undisturbed Specimens

Soil Location and I.D.	Critical Shear Stress dynes/cm^2	Rate of Change of Erosion Rate (gm/dyne·min)10^4
Albuquerque District AL-2	35-37	14.0
Albuquerque District LJ-1	36-40	115.0
Albuquerque District LJ-2	6-9	106.7
Fort Worth District AQU-2	3-4	160.0
Fort Worth District TRI-1	18-26	16.0
Galveston District NUE-12	36-40	128.0
Kansas City District DEL-1	20-32	N.A
Kansas City District WAK-30	2-3	82.4
Little Rock District ARK-B	3-5	92.0
Little Rock District BLK-A	40-42	N.A.
Los Angeles District EIC-1	1-3	140.0
Los Angeles District EIC-2	2-4	21.0
Memphis District WHT-142	3-5	128.0
Memphis District WHT-143	>40	N.A.
Mobile District TOM-AB	15-40	N.A.

(Continued)

Table 7 (Concluded)

Soil Location and I.D.	Critical Shear Stress dynes/cm^2	Rate of Change of Erosion Rate (gm/dyne·min)10^4
New Orleans District MIS-L	16-23	36.7
New Orleans District MIS-R	32-35	13.2
Omaha District JAM-1	10-13	41.9
Omaha District JAM-4	13-17	150.0
Philadelphia District WC-20	1-3	9.2
Sacramento District SAC-169	4-6	42.4
Sacramento District SAC-179	3-4	295.4
St. Louis District MIS-CB	3-5	754.5
St. Louis District MIS-WH	5-6	39.1
San Francisco District DRY-4	3-4	450.0
San Francisco District EEL-6	10-12	27.0
Savannah District OLI-1	39-40	55.0
Savannah District OLI-2	2.5-3.5	220.0
Tulsa District CAN-67	15-18	17.7
Tulsa District VER-36	28-38	8.9

Table 8

Index Properties of Remolded Samples Tested in Rotating Cyclinder

Soil Location and I.D.		Conditions After Consolidation				
		Wet Unit weight lb/cu ft	Moisture Content %	Dry Unit weight lb/cu ft	Void Ratio	Degree of Saturation %
Albuquerque District						
AL-2	#2	118.26	30	90.97	.78	99.6
	#1	120.54	30	92.73	.75	100.0
	#3	120.19	30	92.45	.75	100.0
Albuquerque District						
LJ-1	#3	121.43	29	94.13	.76	100.0
	#1	120.23	30	92.49	.79	100.0
	#2	120.28	29	93.24	.78	98.9
Albuquerque District						
LJ-2	#2	121.54	29	94.21	.77	100.0
	#1	120.63	30	92.80	.80	100.0
	#3	120.07	30	92.36	.80	99.6
Fort Worth District						
AQU-2	#3	115.46	34	86.16	.93	97.2
	#2	114.85	34	85.71	.94	96.2
	#1	116.27	34	86.77	.92	98.7
Fort Worth District						
TRI-1	#1	121.23	25	96.98	.68	96.0
	#2	121.34	25	97.07	.68	96.3
	#3	121.29	25	97.03	.68	96.2

(Continued)

Table 8 (Continued)

Soil Location and I.D.		Conditions After Consolidation: Wet Unit weight lb/cu ft	Moisture Content %	Dry Unit weight lb/cu ft	Void Ratio	Degree of Saturation %
Galveston District						
NUE-12	#1 Redone	108.72	43	76.02	1.16	97.6
	#3	106.22	50	70.81	1.32	99.8
	#2	105.66	52	69.51	1.36	100.0
Kansas City District						
DEL-1	#3	116.01	32	87.9	.86	97.5
	#1	115.51	33	86.8	.88	97.9
	#2	116.76	32	88.46	.85	98.8
Kansas City District						
WAK-30	#2	118.10	32	89.47	.86	99.1
	#3	118.60	31	90.54	.84	98.5
	#1	119.12	31	90.93	.83	99.5
Little Rock District						
ARK-B	#3	125.01	28	97.66	.72	100.0
	#1	121.37	28	94.82	.77	97.8
	#2	120.15	28	93.86	.79	95.5
Little Rock District						
BLK-A	#3	122.31	24	98.64	.68	93.5
	#1	124.27	24	100.22	.66	97.3
	#2	121.93	25	97.54	.70	94.8

(Continued)

Table 8 (Continued)

Soil Location and I.D.	Conditions After Consolidation				
	Wet Unit weight lb/cu ft	Moisture Content %	Dry Unit weight lb/cu ft	Void Ratio	Degree of Saturation %
Los Angeles District					
EIC-1 #2	118.82	32	90.01	.86	99.5
#3	119.67	30	92.05	.82	98.0
#1	119.81	30	92.16	.82	98.3
Los Angeles District					
EIC-2 #3	128.50	24	103.63	.61	100.0
#2	125.02	25	100.02	.67	100.0
#1	124.57	24	100.46	.66	97.3
Memphis District					
WHT-142 #3	104.74	45	72.23	1.33	91.2
#1	108.30	43	75.74	1.22	94.8
#2	108.39	40	77.42	1.18	91.8
Memphis District					
WHT-143 #1	119.13	29	92.35	.80	96.7
#3	119.52	29	92.65	.79	97.5
#2	119.33	29	92.50	.79	97.1
Mobile District					
TOM-AB #3 Redo	113.13	39	81.30	1.03	100.0
#1 Redo	108.66	38	78.74	1.10	91.5
#2 Redo	113.30	38	82.10	1.01	99.3

(Continued)

Table 8 (Continued)

Soil Location and I.D.	Conditions After Consolidation				
	Wet Unit weight lb/cu ft	Moisture Content %	Dry Unit weight lb/cu ft	Void Ratio	Degree of Saturation %
New Orleans District					
MIS-L #2 Redo	101.71	54	66.05	1.45	95.4
#1	105.79	51	70.06	1.35	99.6
#3	107.02	51	70.88	1.32	100.0
New Orleans District					
MIS-R #2	114.30	31	87.25	.88	92.5
#3	117.18	31	89.45	.83	97.7
#1	118.06	32	89.44	.83	100.0
Omaha District					
JAM-1 #2	111.01	41	78.73	1.12	97.7
#3	111.44	42	78.48	1.13	99.5
#1	110.54	42	77.85	1.15	98.0
Omaha District					
JAM-4 #3	108.52	44	75.36	1.17	98.6
#2	108.67	43	76.00	1.15	97.9
#1	109.21	44	75.84	1.16	99.7
Philadelphia District					
WC-20 #2	120.56	34	89.97	.89	100.0
#3	121.62	31	92.84	.83	100.0
#1	120.50	31	91.98	.85	99.8

(Continued)

Table 8 (Continued)

Soil Location and I.D.	Conditions After Consolidation				
	Wet Unit weight lb/cu ft	Moisture Content %	Dry Unit weight lb/cu ft	Void Ratio	Degree of Saturation %
Sacramento District					
SAC-169 #2	121.40	31	92.67	.84	100.0
#3	120.84	30	92.96	.83	98.4
#1	121.23	30	93.26	.83	99.1
Sacramento District					
SAC-179 #3	121.39	28	94.84	.78	96.9
#2	122.42	31	93.45	.81	100.0
#1	121.89	27	95.98	.76	96.0
St. Louis District					
MIS-CB #B Redone	120.73	31	92.16	.84	100.0
#D Redone	118.40	31	90.39	.87	96.5
#A Redone	120.58	29	93.47	.81	97.1
St. Louis District					
MIS-WH #2 Redone	118.19	32	89.54	.85	100.0
#D Redone	113.73	36	83.63	.98	97.6
#B Redone	114.57	38	83.02	.99	100.0
San Francisco District					
DRY-4 #1	124.28	29	96.34	.76	100.0
#2	120.08	28	93.81	.80	94.5
#3	119.23	27	93.88	.80	91.3

(Continued)

Table 8 (Concluded)

Soil Location and I.D.		Conditions After Consolidation: Wet Unit weight lb/cu ft	Moisture Content %	Dry Unit weight lb/cu ft	Void Ratio	Degree of Saturation %
San Francisco District						
EEL-6	#3	123.13	27	96.95	.74	98.8
	#2 Redone	124.14	27	97.75	.72	100.0
	#2	122.92	27	96.79	.74	98.4
Savannah District						
OLI-1	#2	108.36	41	76.85	1.17	93.7
	#1	113.19	38	82.02	1.03	98.4
	#3	112.51	39	80.94	1.06	98.4
Savannah District						
OLI-2	#1 Redone	115.84	35	85.81	.93	100.0
	#1	116.15	35	86.04	.92	100.0
	#3	115.69	35	85.70	.93	99.8
Tulsa District						
CAN-67	#3	118.59	31	90.52	.83	98.9
	#2	118.96	30	91.51	.81	98.1
	#1	119.55	30	91.96	.80	99.1
Tulsa District						
VER-36	#3	122.73	28	95.88	.74	100.0
	#2	121.86	28	95.20	.76	99.2
	#1	120.68	28	94.28	.77	97.0
	#1 Redone	119.16	29	92.37	.81	95.9

Table 9

Results of Rotating Cylinder Tests on Saturated Remolded Specimens

Soil Location and I.D.	Total Salts, meq/l		Critical Shear Stress dynes/cm^2	Rate of Change of Erosion Rate (cm/dyne·min)10^4
	River Water	Eroding Fluid		
Albuquerque District				
AL-2 #2	4.1	Distilled Water	1.4	12.60
#1	4.1	2.05	11.0	3.20
#3	4.1	4.1	22.5	2.70
Albuquerque District				
LJ-1 #3	26.5	Distilled Water	10.0	1.30
#1	26.5	13.25	42.0	0.87
#2	26.5	26.5	34.0	0.36
Albuquerque District				
LJ-2 #2	26.5	Distilled Water	0.0	*
#1	26.5	13.25	0.0	*
#3	26.5	26.5	0.0	*
Fort Worth District				
AQU-2 #3	12.2	Distilled Water	20.0	0.18
#2	12.2	2.04	>131.0	N.A.
#1	12.2	6.11	>115.0	N.A.
Fort Worth District				
TRI-1 #1	8.5	Distilled Water	0.0	*
#2	8.5	4.25	0.0	*
#3	8.5	8.5	0.0	*
Galveston District				
NUE-12 #1 Redone	48.0	Distilled Water	0.0	20.0
#3	48.0	7.992	-	-
#2	48.0	23.98	>68.0	N.A.

(Continued)

* Sample disintegrated

Table 9 (Continued)

Soil Location and I.D.	Total Salts, meq/l		Critical Shear Stress dynes/cm^2	Rate of Change of Erosion Rate (gm/dyne·min)10^4
	River Water	Eroding Fluid		
Kansas City District				
DEL-1 #3	2.9	Distilled Water	6.5	0.94
#1	2.9	1.45	42.0	0.28
#2	2.9	2.9	>61.5	N.A.
Kansas City District				
WAK-30 #2	5.4	Distilled Water	0.0	2.7
#3	5.4	0.90	4.0	0.27
#1	5.4	2.698	>104.0	N.A.
Little Rock District				
ARK-B #3	2.5	Distilled Water	0-1	8.60
#1	2.5	1.25	9.0	5.9
#2	2.5	2.5	8.0	1.30
Little Rock District				
BLK-A #3	1.3	Distilled Water	22.0	1.60
#1	1.3	0.65	28.0	0.53
#2	1.3	1.3	>50.0	N.A.
Los Angeles District				
EIC-1 #2	24.0	Distilled Water	0.0	18.70
#3	24.0	4.72	>119.0	N.A.
#1	24.0	11.80	>125.0	N.A.

(Continued)

Table 9 (Continued)

Soil Location and I.D.	Total Salts, meq/l River Water	Total Salts, meq/l Eroding Fluid	Critical Shear Stress dynes/cm^2	Rate of Change of Erosion Rate (gm/dyne·min)10^4
Los Angeles District				
EIC-2 #3	24.0	Distilled Water	0.0	0.37
#2	24.0	4.0	60.0	N.A.
#1	24.0	12.0	>111.0	N.A.
Memphis District				
WHT-142 #3	1.6	Distilled Water	0.0	N.A.
#2	1.6	0.79	0.0	N.A.
#1	1.6	1.58	0.0	N.A.
Memphis District				
WHT-143 #1	1.7	Distilled Water	0.0	30.00
#3	1.7	0.851	30.0	0.11
#2	1.7	1.702	>140.0	N.A.
Mobile District				
TOM-AB #3 Redo	0.59	Distilled Water	0.0	3.90
#1 Redo	0.59	0.33	2.0	0.56
#2 Redo	0.59	0.66	13.0	0.51
New Orleans District				
MIS-L #2 Redo	2.85	Distilled Water	6.0	3.39
#1	2.85	1.428	>16.0	N.A.
#3	2.85	2.856	>120.0	N.A.

(Continued)

Table 9 (Continued)

Soil Location and I.D.		Total Salts, meq/l River Water	Total Salts, meq/l Eroding Fluid	Critical Shear Stress, dynes/cm^2	Rate of Change of Erosion Rate, (gm/dyne·min)10^4
New Orleans District					
MIS-R	#2	2.85	Distilled Water	3.0	4.30
	#3	2.85	0.476	>118.0	N.A.
	#1	2.85	1.428	>108.0	N.A.
Omaha District					
JAM-1	#2	12.5	Distilled Water	0.0	1.70
	#3	12.5	2.01	>120.0	N.A.
	#1	12.5	6.04	>118.0	N.A.
Omaha District					
JAM-4	#3	13.5	Distilled Water	5.0	0.57
	#2	13.5	2.25	80-90	N.A.
	#1	13.5	6.75	>120.00	N.A.
Philadelphia District					
WC-20	#2	1.48	Distilled Water	3.5	6.51
	#3	1.48	0.235	3.0	3.70
	#1	1.48	0.705	3.5	3.40
Sacramento District					
SAC-169	#2	1.4	Distilled Water	0.0	32.00
	#3	1.4	0.69	5.0	2.27
	#1	1.4	1.38	16.0	2.60

(Continued)

Table 9 (Continued)

Soil Location and I.D.		Total Salts, meq/l: River Water	Total Salts, meq/l: Eroding Fluid	Critical Shear Stress dynes/cm^2	Rate of Change of Erosion Rate (gm/dyne·min)10^4
Sacramento District					
SAC-179	#3	1.4	Distilled Water	0.0	20.00
	#2	1.4	0.69	1.0	2.30
	#1	1.4	1.38	5.0	0.64
St. Louis District					
MIS-CB	#B Redone	3.4	Distilled Water	0.0	5.20
	#D Redone	3.4	0.565	15.0	0.37
	#A Redone	3.4	1.70	>119.0	N.A.
St. Louis District					
MIS-WH	#2 Redone	3.6	Distilled Water	21.0	1.45
	#D Redone	3.6	0.572	17.0	0.25
	#B Redone	3.6	1.715	>115.0	N.A.
San Francisco District					
DRY-4	#1	2.5	Distilled Water	*	N.A.
	#2	2.5	2.54	*	N.A.
	#3	2.5	3.81	9.0	7.50
San Francisco District					
EEL-6	#3	2.6	Distilled Water	0.0	16.00
	#2 Redone	2.6	1.3	15.0	8.40
	#2	2.6	2.6	12.5	2.40

(Continued)

* Slumping failure - not testable

Table 9 (Concluded)

Soil Location and I.D.	Total Salts, meq/l		Critical Shear Stress dynes/cm^2	Rate of Change of Erosion Rate (gm/dyne·min)10^4
	River Water	Eroding Fluid		
Savannah District				
OLI-1 #2	0.41	Distilled Water	0.0	20.00
#1	0.41	0.2	1.0	6.9
#3	0.41	0.4	5.0	3.0
Savannah District				
OLI-2 #1 Redone	0.41	Distilled Water	0.0	1.46
#1	0.41	0.2	25.0	4.10
#3	0.41	0.4	23.0	1.03
Tulsa District				
CAN-67 #3	5.9	Distilled Water	0.0	4.50
#2	5.9	0.952	6.0	0.72
#1	5.9	2.85	>60.0	N.A.
Tulsa District				
VER-36 #3	3.2	Distilled Water	1.0	5.00
#2	3.2	0.537	4.0	1.90
#1	3.2	1.61	20.0	0.19
#1 Redone	3.2	3.22	48.0	0.10

Table 10
Chemical Properties of Soil Tested - Repeat Series*

Soil Location and I.D.		Soil Pore Water Paste meq/l pH	Na	Mg	Ca	Total Salts meq/l	SAR
Galveston District							
NUE-12	#2	7.4	23.5	5.75	5.75	38.5	9.8
	#3	7.2	25.0	6.5	6.5	40.5	9.8
	#1	7.2	20.5	5.75	5.75	35.5	8.5
Little Rock District							
ARK-B	#2	7.4	0.54	2.6	2.6	6.6	0.3
	#1	7.4	0.55	2.45	2.45	6.4	0.4
	#3	7.4	0.54	2.48	2.48	6.4	0.3
Los Angeles District							
EIC-2	#1	8.2	3.4	2.4	2.4	10.3	2.2
	#3	7.7	3.7	2.3	2.3	10.3	2.4
	#2	7.7	3.7	2.3	2.3	10.3	2.4
Omaha District							
JAM-4	#2	7.2	2.15	8.5	8.5	28.0	0.7
	#3	7.2	2.10	10.0	10.0	29.0	0.7
	#1	7.2	2.35	9.0	9.0	28.5	0.8

(Continued)

* All chemical measurements taken from consolidation squeezings.

Table 10 (Concluded)

Soil Location and I.D.		Soil Pore Water Paste meq/l pH	Na	Mg	Ca	Total Salts meq/l	SAR
Sacramento District							
SAC-169	#4	7.5	.44	2.75	2.75	6.3	.3
	#2	7.4	.45	2.15	2.15	6.1	.3
	#5	7.6	.47	3.00	3.00	7.5	.3
	#3	7.3	.51	2.40	2.40	7.0	.3
	#6	7.5	.45	3.30	3.30	7.9	.2
Savannah District							
OLI-1	#1	7.2	.34	.33	.33	1.7	.6
	#2	7.4	.19	.49	.49	1.7	.3
	#5	7.6	.19	.43	.43	2.1	.3
	#3	7.4	.19	.49	.49	1.9	.3
	#4	7.4	.35	.48	.48	1.9	.5
	#6	7.5	.21	.49	.49	1.8	.3

Table 11

Index Properties of Remolded Samples Tested in Rotating Cylinder-Repeat Series

Soil Location and I.D.		Conditions After Consolidation: Wet Unit Weight lb/cu ft	Moisture Content %	Dry Unit Weight lb/cu ft	Void Ratio	Degree of Saturation %
Galveston District						
NUE-12	#2	110.52	36	81.3	1.02	93
	#3	110.71	37	80.8	1.03	94
	#1	111.24	36	81.8	1.01	94
Little Rock District						
ARK-B	#2	113.09	28	88.4	.90	84
	#1	118.07	29	91.5	.83	94
	#3	120.24	29	93.2	.80	98
Los Angeles District						
EIC-2	#1	123.05	26	97.3	.71	99
	#3	122.19	25	98.1	.70	93
	#2	122.68	26	97.3	.71	98
Omaha District						
JAM-4	#2	108.55	44	75.4	1.17	99
	#3	108.50	43	75.9	1.15	98
	#1	108.77	44	75.5	1.16	99

(Continued)

Table 11 (Concluded)

Soil Location and I.D.		Conditions After Consolidation				
		Wet Unit weight lb/cu ft	Moisture Content %	Dry Unit weight lb/cu ft	Void Ratio	Degree of Saturation %
Sacramento District						
SAC-169	#4	119.97	31	91.7	.86	98
	#2		32			
	#5	120.75	30	92.7	.84	98
	#3	120.98	29	93.6	.82	98
	#6	118.54	30	91.1	.87	94
Savannah District						
OLI-1	#1	117.07	31	89.3	.86	97
	#2	116.87	33	88.0	.89	98
	#5	120.66	28	94.5	.76	97
	#3	118.15	33	88.6	.89	100
	#4	120.16	29	93.0	.79	99
	#6	120.83	29	94.0	.77	99

Table 12

Influence of Soaking Fluid Concentration on Erodibility

Soil Location And I.D.	Total Salts, meq/l			Eroding Fluid As Soaking Fluid		Total Salts meq/l
	River Water	Eroding Fluid	Eroding Fluid As Soaking Fluid	Critical Shear Stress, $dynes/cm^2$	Rate of Change Of Erosion Rate $(gm/dyne\text{-}min)10^4$	Pore Fluid As Soaking Fluid
Galveston District		Distilled	Distilled			
NUE-12 #1 Redone,#2*	48.0	Water	Water	0.0	20	38.2
#3 ,#	48.0	8.0	8.0	---------	------	38.2
#2 ,#	48.0	24.0	24.0	>68.0	NA	38.2
Little Rock District		Distilled	Distilled			
ARK-B #3 ,#2	2.5	Water	Water	0-1	8.6	6.5
#1 ,#1	2.5	1.25	1.25	9.0	5.9	6.5
#2 ,#3	2.5	2.50	2.50	8.0	1.3	6.5
Los Angeles District		Distilled	Distilled			
EIC-2 #3 ,#1	24.0	Water	Water	0.0	0.37	10.3
#2 ,#3	24.0	4.0	4.0	60.0	NA	10.3
#1 ,#2	24.0	12.0	12.0	>111.0	NA	10.3
Omaha District		Distilled	Distilled			
JAM-4 #3 ,#2	13.5	Water	Water	5.0	.57	28.5
#2 ,#3	13.5	2.25	2.25	80-90	NA	28.5
#1, ,#1	13.5	6.75	6.75	>120.0	NA	28.5
Sacramento District		Distilled	Distilled			
SAC-169 #2 ,#4	1.4	Water	Water	0.0	32.00	6.9
#3 #2,#5	1.4	0.69	0.69	5.0	2.27	6.9
#1 #3,#6	1.4	1.38	1.38	16.0	2.60	6.9
Savannah District		Distilled	Distilled			
OLI-1 #2 ,#5	0.41	Water	Water	0.0	20.0	1.9
#1	0.41	0.2	0.2	1.0	6.9	1.9
#3 ,#6	0.41	0.4	0.4	5.0	3.0	1.9

(Continued)

* #(First Series), #(Repeat Series)

Table 12 (Concluded)

Soil Location And I.D.	Pore Fluid As Soaking Fluid: Critical Shear Stress dynes/cm^2	Rate of Change of Erosion Rate (gm/dyne-min)10^4	$\Delta\varepsilon_o$	Finer Than .002/mm %	Predicted Critical Shear Stress dynes/cm^2
Galveston District					
NUE-12 #1 Redone #2	>130.0	NA	47	53	8-11
#3 ,#1	>142.0	NA	47	53	
#2 ,#3	>135.0	NA	47	53	
Little Rock District					
ARK-B #3 ,#3	∿10-15	---	9	17	3-4
#1 ,#1	40.0	6.9	9	17	
#2 ,#2	∿50.0	6-7	9	17	
Los Angeles District					
EIC-2 #3	10.5	.3	18	25	4-6
#2	>144	NA	18	25	
#1	>143	NA	18	25	
Omaha District					
JAM-4 #3	18.0	.15	17	40	10-20
#2	143.0	NA	17	40	
#1	142.0	NA	17	40	
Sacramento District					
SAC-169#2	21.5	13.2	22	14	3-4
#3	45.0	13.8	22	14	
#1	59.0	17.5	22	14	
Savannah District					
OLI-1 #2	0.0	.82	14	29	2-3
#1	---	---	14	29	
#3	0.0	.82	14	29	

APPENDIX E: PRELIMINARY ANALYSIS OF ALL THE SOILS AND FIRST YEAR'S TESTING OF THIRTY SELECTED SOILS

Preliminary Analysis of All the Soils

Preparation of a soil paste

1. A number of the tests performed require that distilled water be added to a disturbed sample of the soil until a saturated soil paste is produced. At saturation, the soil paste glistens as it reflects light, flows slightly when container is tipped and slides freely and cleanly off a spatula for all soils, except those with high clay content. After mixing, the soil paste is allowed to stand for an hour or more to ensure uniformity of water content and pore fluid chemistry before proceeding with the testing.

Hydrometer analysis

2. The standard analysis procedure for determining the grain size distribution of fine grained soils was followed, including use of a dispersant and mechanical agitation provided by mixing the soil-water suspension for 15 minutes in an electric milk shake blender. The dispersing agent used is 10 ml of 5% by weight tri-sodium phosphate (N_aPO_4) added to 1000 ml of soil-water suspension. Of particular interest from the standard hydrometer analysis is the percent weight finer than the 0.005 mm and the percent finer than 0.002 mm (percent clay) of each soil.

Determination of the magnitude of dielectric dispersion, $\Delta\epsilon_o$, on remolded samples

3. Arulanandan et al. (12) first proposed the determination of magnitude of dielectric disperions as a quantitative method to characterize natural soils in terms of clay type and amount. The magnitude of dielectric dispersion is defined as the decrease in apparent dielectric constant when the frequency of an alternating current passing through a saturated soil sample is increased from 5 to 50 mega cycles per second. The apparent dielectric constant can be calculated from the following equation:

$$\epsilon = \frac{Cd}{\epsilon_v A} \qquad \text{E.1}$$

where: C = measure true capacitance of the saturated soil sample

d = length of soil sample

A = cross-sectional area of soil sample

ε_v = dielectric constant of a vacuum (8.85×10^{-14} farad/cm)

The dielectric constant is actually a measure of the ability of the sample to store electrical potential energy on charged clay surfaces under the influence of an electric field.

4. A saturated remolded soil sample is obtained by mixing the sample to a saturated soil paste and placing it into a thin cylindrical teflon sleeve so to avoid creating air voids. The sample is then trimmed flush to the sleeve ends, and the sleeve is cleaned on the outside and placed in a teflon cell assembly. The cell assembly has platinum coated electrodes and is described in detail by Arulanandan et al. (12)

5. All capacitance and resistance measurements were made while the sample was contained in the teflon cell with an Rx meter, type 250 (Boonton Radio Corporation, Division of Hewlett-Packard, New Jersey), at frequencies of 5 and 50 megahertz. This instrument is essentially a schering bridge with an oscillator, amplifier-detector and null indicators designed to measure equivalent parallel conductance in the range of 0.0 to 0.067 mhos, at frequencies of 0.5 to 250 megahertz. Moisture content determinations were taken on the samples after making electrical readings. A detailed description of the equipment and measurement techniques can be found in previous works (5, 6, 8, 12).

Chemical analysis of pore fluid

6. An extract to represent the pore fluid of the undisturbed soil samples is obtained by mixing soil from the disturbed soil samples to a saturated soil paste, allowing it to stand for an hour or more, then transferring it to a buchner funnel. The extract is vacuum drained through a clean filter paper and collected. Enough saturated sample extract is needed for pore fluid cation type and amount determinations and undisturbed sample soaking for free swell and slaking tests.

Sodium adsorption ratio (SAR) and
potasium (K) concentration

7. The separate amounts of $C_a^{++} + M_g^{++}$, K^+, and N_a^+ in meq/l are measured using specific ion electrodes connected to a Beckman Expandomatic pH meter. Millivolt readings of the meter are calibrated to salt concentrations using various concentrations of $C_a^{++} + M_g^{++}$, K^+, and N_a^+ standardized solutions. A divalent Orion specific ion electrode is used to determine $C_a^{++} + M_g^{++}$ concentrations, a Beckman electrode for N_a^+ concentrations and an Orion electrode for K^+ concentrations.

The sodium adsorption ratio is calculated using the following equation:

$$SAR = \frac{N_a^+}{\sqrt{\frac{C_a^{++} + M_g^{++}}{2}}}$$

where concentrations are in terms of meq/l.

Chemical analysis of eroding fluid

9. Salt concentration determinations of eroding fluid are made directly on river water samples sent with each soil sample. The measurement procedure is identical to that used for the pore fluid extract salt determinations.

pH readings are taken on the river water samples with a Beckman Expandomatic pH meter.

pH measurment of saturated soil paste

10. A Beckman Expandomatic pH meter is used to make pH readings of saturated soil pastes. The electrodes are placed directly into the soil paste.

Cation-exchange capacity determination

11. The method used to determine the soil cation-exchange capacity is given as procedure 19 in the Agriculture Handbook No. 60, United States Department of Agriculture (13).

12. About 4 to 6 grams of air dried disturbed soil of known moisture content is weighed and added to a 50 ml conical centrifuge tube along with 33 ml of 1N sodium acetate. The mixture is shaken for 5 minutes then centrifuged at 1000 RCF until the supernatant liquid is clear. The clear liquid is then poured off and again 33 ml of sodium acetate is added. The mixture is again shaken and centrifuged. This is repeated a total of four times to saturate the

cation-exchange sites. The same sample treatment is again repeated three more times using 33 ml of 95 percent ethanol added each time instead of sodium acetate. This serves to rinse sodium from the soil which is not associated with cation-exchange sites. The electrical conductivity of the supernatant from the third washing should be less than 40 micromhos/cm.

The absorbed sodium is then replaced by extraction with three 33 ml portions 1N Ammonium acetate, collecting the supernatant each time. The sodium concentration of the combined extracts is determined, after dilution to 100 ml with distilled water, using the Beckman Expandomatic pH meter and the Beckman sodium specific ion electrode as done in the analysis of the pore and eroding fluids. The cation-exchange capacity of the soil in terms of meq per 100 grams dry weight of soil was calculated using the following equation:

$$\text{Cation-exchange capacity} = \frac{(N_a^+ \text{ concentration in meq/l})(10)}{(\text{wt. of sample in grams})}$$

Free swell tests

14. Undisturbed soil samples are obtained by forcing a 3 inch outside diameter thin-walled (0.035 inch wall thickness) aluminum tubing with a sharpened edge into undisturbed soil and trimming the sample to a 3/16 inch thick section. The tubing is then placed in a beaker with the bottom soil surface resting on a filter paper and porous stone. The beaker is filled with enough pore fluid solution, obtain by vacuum extraction of a soil paste, to saturate the soil from the bottom up as much as possible.. The soil section is then extruded from the tube and placed on a filter paper. The sample and filter paper is placed on sponges saturated in distilled water. A dessicator with a moisture saturated atmosphere is used to prevent evaporation from the soil surface and from the sponges, keeping the distilled water surface in full contact with the base of the soil samples throughout the test.

15. The samples are lifted from the sponges periodically with a thin brass rod grid apparatus to be weighed, then are returned to the saturated sponges. This is repeated twice a day until a constant or maximum weight is reached. While the samples rest on the sponges, the brass grid sits in a narrow recess cut into the sponges to keep the grid from touching the sample. Equilibrium generally requires four days. After the water uptake equilibrium

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UNCLASSIFIED WES/TR/GL-80-5 NL

was reached, the samples were oven dried to determine the quantity of dried soil. The weight of the dried filter paper was subtracted from the total weight after drying. Free swell results are expressed as grams of water uptake per 100 grams of oven dry soil.

First Year's Testing of 30 Selected Soils

Undisturbed dry density and moisture content determination

16. Undisturbed density is determined by forcing a thin-walled circular tubing with a sharpened edge into an undisturbed sample, trimming the soil in the tubing to a known volume and weighing it.

17. A moisture content determination is made on soil extruded from the tubing and was dried at 100°C for at least 24 hours.

Specific gravity tests.

18. The standard procedure presented in the Soil Testing Laboratory Manual at the University of California at Davis Soil Mechanics Laboratory is used. The soil particle specific gravity, G_s, is calculated using the following equation:

$$G_s = \frac{W_s}{W_s + W_{bw} - W_{bws}}$$

where W_s = dry weight of sample

W_{bws} = weight of flask + sample + water at temperature T°C

W_{bw} = weight of flask + water at T°C (from calibration curve).

Atterberg limit tests

19. The standard procedure presented in the Soil Testing Laboratory Manual at the University of California at Davis Soil Mechanics Laboratory is used.

Organic content determination

20. Organic content determinations are first made on disturbed soil samples. Later the tests were repeated on undisturbed samples. The test procedure was the same for each.

21. About 60 grams moist soil is oven dried at 100°C for at least 24 hours and weighed. The organics are then burned out by keeping the soil in a high heat oven at 600°C. The sample is weighed daily until a constant weight is achieved. This usually requires about four days. The organic content is defined as the ratio of the weight lost by the sample during burning in the high heat oven divided by the original dry weight of the soil after drying at 100°C.

Gypsum content determination

22. With only slight variations, the procedure followed to determine gypsum content is that given as procedure 22b in the Agriculture Handbook No. 60, United States Department of Agriculture.

23. A filtered fluid extract from the soil is obtained by adding 45 ml distilled water to about 30 grams air-dried soil in a clean plastic bottle, sealing and shaking the bottle for fifteen minutes, and vacuuming the extract through a clean filter paper with a buchner funnel. The moisture content of the soil is determined to calculate the dry weight of the soil used.

24. Twenty ml of the filtered extract is mixed with 20 ml of acetone in a 50 ml conical centrifuge tube and let stand for 10 minutes to allow for precipitate to flocculate. After the solution is centrifuged at 1000 RCF for 5 minutes, the supernatant is poured off and the tube is allowed to drain for 5 minutes, inverted on a clean filter paper. The precipitate is then dispersed and the inside walls of the tube are rinsed with a stream of 10 ml of acetone, blown from a pipet. Again the solution is centrifuged and drained. Exactly 40 ml of distilled water is added to the tube and the tube is sealed and shaken until the precipitate is dissolved. The electrical conductivity of the solution is determined using the Beckman Conductivity Bridge Model RC 16 BZ. The conductivity reading is corrected to 25°C and applied to relationships between $CaSO_4$ concentration in meq/l and conductivity at 25°C given in Agriculture Handbook No. 60 (13). The amount of gypsum in meq per 100 grams dry soil weight is given by the following equation:

$$\frac{\text{Meq. of } CaSO_4}{100 \text{ grams soil}} = \frac{\left[\begin{array}{l}\text{Meq. of } CaSO_4 \\ \text{from conductivity} \\ \text{reading}\end{array}\right] \times \left[\begin{array}{l}\text{ml. of water} \\ \text{used to dissolve} \\ \text{precipitate}\end{array}\right] \times \left[\begin{array}{l}\text{ml. water added} \\ \text{to soil to get} \\ \text{original extract}\end{array}\right]}{10 \times \text{grams dry weight of soil used}}$$

Dispersion ratio test

25. In addition to performing a standard hydrometer analysis on each of the 30 selected soils, a variation of the test was also performed on each soil. The second hydrometer analysis is indentical to the first except for the following change. During the second analysis, no dispersing agent is used and the distilled water-soil suspension is only shaken end over end for 20 times. Middleton (10) defined the dispersion ratio by the following equation:

$$\text{Degree of dispersions} = \frac{\text{percent finer than 0.005 mm without chemical dispersant or mechanical agitation}}{\text{percent finer than 0.005 mm with chemical dispersant and mechanical agitation}}$$

Determination of magnitude of dielectric dispersion, $\Delta\epsilon_o$, on saturated undisturbed samples

26. Saturated undisturbed samples are obtained by pressing a thin teflon cylindrical sleeve with a sharp cutting edge adaptor into a larger undisturbed soil sample, then saturating the sample from the bottom up with distilled water as much as possible. The teflon sleeve sample is then removed from the larger undisturbed soil sample, the cutting edge adaptor is removed, the sample is trimmed flush with the sleeve ends and the teflon sleeve is cleaned on the outside and placed in a teflon cell assembly. The rest of the procedure is the same as followed to determine the magnitude of dielectric dispersion of saturated remolded samples.

Slake tests on saturated undisturbed samples

27. Slake tests were performed only on the 24 samples which had a clay content of 15 percent or greater.

28. Apparatus. During testing the sample rests on a copper wire grid apparatus. The wire grid is submerged with the sample in a 1000 ml glass beaker filled with 700 ml of distilled water. The wire grid assembly can be lifted from the beaker, but is supported to a fixed stand in such a way that when lowered it always comes to the same position. The beaker has a clear plastic top to prevent evaporation weight-loss during long term tests with a small hole to pass the wire mesh support and rests on a Mettler P1200 balance. The buoyant weight of soil particles which fall from the sample through the wire grid is recorded from the Mettler balance reading.

29. Sample preparation. Two inch long samples are obtained by pressing a 3.5 cm diameter thin-walled, sharp-edged tubing into a larger undisturbed soil sample. The tubing is removed from the larger sample, placed in a beaker and saturated with its soil paste extract pore fluid from the bottom up as much as possible. Upon saturation a 1 cm thick section is extruded and trimmed from the center of the 2 inch sample. A moisture content determination is made on part of the saturated soil trimmed away from the original 2 inch long sample. The 1 cm thick by 3.5 cm diameter sample is weighed and tested as soon as possible to prevent drainage or evaporation of water from the sample.

30. Testing procedure. The empty wire grid sample holder is immersed in 700 ml of distilled water contained in the beaker and a balance reading is made. This is the total weight of the beaker, the beaker cover, the water weight and the weight of the water displaced by the wire mesh apparatus. This reading is labeled W_1. The weight of the saturated trimmed sample is labeled W_2. The wire grid is lifted from the beaker, the saturated 3.5 cm diameter by 1 cm thick undisturbed soil sample is placed on the wire grid and the grid assembly is lowered with the sample back down into the beaker. As soon as the grid is fully lowered, a balance reading is immediately taken. This reading is labeled W_3. Additional balance readings are taken at various intervals until either the sample slakes completely, falling entirely through the wire grid, or until an equilibrium takes place when the slaking process ceases.

31. The slaking rate is characterized by the normalized weight loss after 15 minutes of testing. The balance reading after 15 minutes of slaking is labeled W_4. The normalized weight loss is the apparent buoyant weight loss divided by the initial buoyant weight of the sample. This can be calculated from the following equation:

$$\text{Normalized weight loss in first 15 minutes} = \frac{W_4 - W_3}{W_2 - (W_3 - W_1)}$$

Although slaking of soil off the sample on to the base of beaker increases the balance reading by the buoyant weight of the fallen soil, the balance reading can be decreased by the weight of distilled water taken on by portions of saturated or nearly saturated sample remaining on the wire grid. This can cause the calculated slaking rate to slightly underestimate the actual slaking rate. The effect of distilled water evaporation from the beaker is considered insignificant for the generally short term tests which prevail.

APPENDIX I: GLOSSARY

Cation-exchange-capacity (CEC). The total amount of exchangeable cations that a soil can retain expressed in milliequivalents per 100 grams of dry soil.

Critical shear stress (τ_c). The hydraulic shear stress, applied to the surface of a soil sample, where the rate of erosion is zero expressed in dynes per square centimetre (dyne per square centimetre = 2.089×10^{-3} pounds per square foot).

Dielectric dispersion ($\Delta\varepsilon_o$). The decrease in the apparent dielectric constant when the frequency of an alternating current passing through a soil sample is increased from 5 to 50 megacycles per second (dimensionless).

Erosion rate ($\dot{\varepsilon}$). The slope of a line which fits a plot of soil erosion versus shear stress expressed in grams per square centimetre x minutes.

Exchangeable cations. Relative amounts of the four main metallic cations (calcium, magnesium, sodium, and potassium) held on the surfaces, edges, and in some clays between the unit cells expressed in milliequivalents per 100 grams of dry soil.

Rate of change of erosion rate (s). The slope of a line which fits a plot of erosion rate versus shear stress expressed in grams per dyne x minutes.

Sodium adsorption ratio (SAR). Defined as

$$SAR = \frac{Na}{\sqrt{0.5(Ca + Mg)}}$$

where Na, Ca, and Mg refer to the concentrations of soluble cations (sodium, calcium, and magnesium, respectively) expressed in milliequivalents per litre.

Soluble cations. Concentration of the four main metallic cations (calcium, magnesium, sodium, and potassium) in the soil pore

water expressed in milliequivalents per litre.

Total dissolved solids (TDS) or total salt concentration. The total concentration of the four main metallic cations (calcium, magnesium, sodium, and potassium) in the soil pore water or eroding fluid expressed in milliequivalents per litre. Normality (N) = concentration (milliequivalents per litre) x 10^{-3} conductivity (millimhos per centimetre) = 0.1 concentration (milliequivalents per litre).

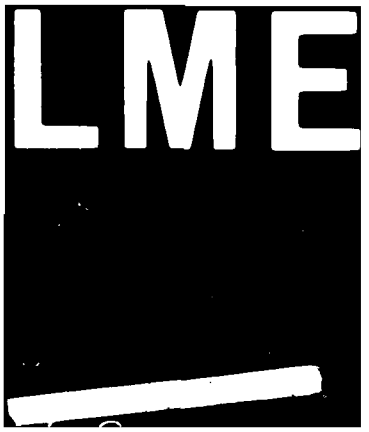
In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Arulanandan, Kandiah
Development of a quantitative method to predict critical shear stress and rate of erosion of natural undisturbed cohesive soils / by Kandiah Arulanandan, Ernest Gillogley, Ryan Tully, Civil Engineering Department, University of California at Davis, Davis, California. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1980.
iv, 41, [54] p. : ill. ; 27 cm. (Technical report - U. S. Army Engineer Waterways Experiment Station ; GL-80-5)
Appendixes A, B, C, D, F, G, and H on microfiche in envelope inside back cover.
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under Contract No. DACW 39-77-C-0080, Task I, Work Unit 04, Authorized by Section 32, Water Resources Development Act, 1974.

(Continued on next card)

Arulanandan, Kandiah
Development of a quantitative method to predict critical shear stress and rate of erosion ... 1980.
(Card 2)

1. Cohesive soils. 2. Hydraulic flume. 3. Rotating cylinder. 4. Streambank erosion. I. Gillogley, Ernest, joint author. II. Tully, Ryan, joint author. III. California. University, Davis. Dept. of Civil Engineering. IV. United States. Army. Corps of Engineers. V. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Technical report ; GL-80-5.
TA7.W34 no.GL-80-5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